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Oil-filled Cables

DEVELOPMENT AND PROGRESS

By A. L. ASHTON B.Sc.(Eng.), M.I.E.E.
Pirelli-General Cable Works, Ltd.

The author traces the progress of oil-filled cable during the past twenty-four years and the operational experience gained over that period with a great variety of installations. The article is based partly on the Chairman's Address to the Southern Centre of The Institution of Electrical Engineers, given by the author in October 1951, *and acknowledgment is made to the Council of the Institution for their permission to make use of some of the information contained therein.*

INTRODUCTION.

THE use of oil-filled cable for high voltage underground power transmission has now become very general in this country and abroad, and it is felt that an account of the development of this type of cable since its early days may be of some interest. This article also describes a number of installations of exceptional interest.

BRIEF HISTORY OF THE DEVELOPMENT OF OIL-FILLED CABLE.

The oil-filled cable was developed by Emanueli in Italy, and a successful trial installation of a cable working at 132 kV was made in that country in 1924.

In 1927 very large installations of 132 kV oil-filled cables were made in the U.S.A., viz. 12 miles in New York and 6 miles in Chicago, each cable being of 90 MVA capacity. The first English installation was a short length of 66 kV feeder consisting of three single-core cables which was installed in 1928 on the North Eastern Electric Supply Company's system.

On the inception of the Grid Scheme the C.E.B. decided to install in the London area approximately 11½ feeder miles of 66 kV oil-filled cables and 27 feeder miles of 132 kV cables. The first of the 66 kV installations was commissioned in 1931 and the first of the 132 kV cables later in the same year. All these cables were of the single-core type. Large installations of 66 kV and 33 kV 3-core cable were shortly afterwards carried out in other parts of the country.

At present there are, in this country, approximately 110 feeder miles of 132 kV cable, 300 miles of 66 kV and 520 miles of 33 kV cable, made by various manufacturers, installed or for which installation contracts are in hand.

The successful operation of the oil-filled cable at high dielectric stress gradients is due to the complete and perfect impregnation of the dielectric with fluid oil, resulting in a cable dielectric free from voids which consequently does not suffer deterioration due to ionisation. Dielectrics of the "solid" type such as that used in lower voltage cables, unfortunately suffer from such deterioration at stresses considerably below the working stresses of oil-filled cables.

HYDRAULIC THEORY AND DESIGN.

The principles of the hydraulic design of an oil-filled cable installation are by now well known and have been fully dealt with elsewhere* and therefore it is assumed that the reader will be familiar with its general principles; however, a brief account of some of the salient features is given.

The cable is provided with longitudinal oil ducts or channels which are in direct communication with the dielectric throughout its length, and which facilitate the thorough impregnation of the cable during manufacture. When the cable is laid, these ducts are connected to external sealed reservoirs or tanks containing degasified oil, which are suitably positioned to control the oil pressure in the cable during heating and cooling cycles by accommodating expansion, and

* "Three-core Oil-filled Cable," by R. E. HORLEY, *G.E.C. Journal*, Vol. V, No. 4, November 1934; also Pirelli-General Oil-filled Cable Handbook.

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feeding back oil on the cooling of the cable.

In single-core cables the oil duct is usually provided in the centre of the conductor which is stranded in the form of a hollow core. In 3-core cables three oil ducts are provided in the " filler " spaces between the cores.

Oil pressures may be steady hydrostatic pressures constant over long periods, upon which are superimposed transient pressures of short duration due to changing load conditions in the cable.

In considering the hydraulic conditions in the cable, the main principles to be borne in mind are that all parts of the cable system must, at all times, be under a positive pressure of oil, i.e. at a pressure above atmospheric; and that the pressure must not at any time exceed the maximum permissible figure for the cable or component concerned.

In present practice the minimum permissible pressure is fixed at 2-3 lb./sq. in., while the maximum pressures vary between 30 and 75 lb./sq. in. under static conditions, and are allowed to rise to well over 100 lb./sq. in. under transient conditions. The steady or ' static ' pressures as they are commonly called, depend on the physical profile of the cable and its steady state of loading, while the transient pressures are related to the rate of absorption or emission of oil, into or out of the cable, due to temperature changes and to the frictional resistance to flow in the oil duct, which in turn is related to the oil viscosity, the size of the duct and the length of the cable.

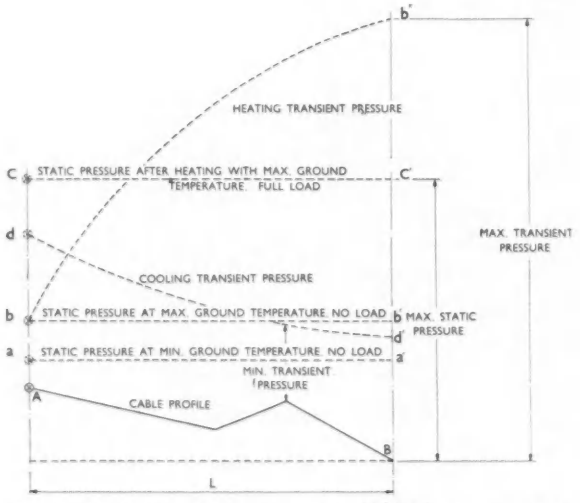


Fig. 1.—Distribution of oil pressures in cable fed by pressure tank.

The transient maximum pressure occurs when switching full load on to a dead cold cable, and the minimum transient when switching all load off a cable carrying approximately 70/80 per cent of full load: these conditions are considered in the design.

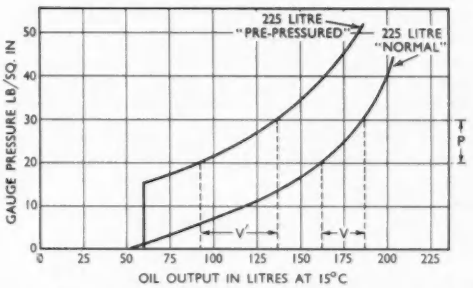


Fig. 2.—Comparison of pressure/volume curves for "normal" and "pre-pressured" type tanks.

The original cables were fed by ' gravity ' type feeding tanks (so called because the tanks were mounted at a physical head above the cable), consisting of flexible-walled cells containing oil at or about atmospheric pressure. As the maximum length of a cable fed in this way from one end only was very limited by the transient pressure conditions, pressure tanks were sometimes installed at the remote end of a cable section to act as a pressure relief during transient conditions, by temporarily accommodating oil emitted from the cable and feeding it back when required, thus enabling longer sections of cable to be fed.

It was frequently necessary to mount these tanks at an elevation above ground level and in view of the problems of accommodation thus created, particularly in congested areas, this method of feeding was discontinued, and since the early 1930's oil feeding has normally been carried out by pressure tanks only.

A pressure tank consists of an oil container accommodating a number of sealed gas-filled cells which contract and expand in accordance with the pressure conditions in the cable.

Fig. 1 shows the distribution of oil pressure in a cable section fed in this manner from one end. In this figure, the line *A-B* re-

presents the cable profile, the three horizontal lines *a-a'*, *b-b'* and *c-c'* indicate the static pressure heads at minimum ground temperature; maximum ground temperature with no load; and at maximum ground temperature with the cable fully loaded, respectively. The maximum heating and minimum cooling transient pressures are indicated by the two curves *b-b''* and *d-d'*. The pressure at any point in the cable is represented by the vertical ordinate between the cable profile and the pressure curve.

The pressure-volume relationships of typical pressure tanks are shown in fig. 2. The lower curve shows the characteristic for a normal type tank, i.e. one in which the cells are assembled at atmospheric pressure. It will be noted that at the high pressure end of this curve, a given volume of oil V admitted (and consequent decrease of gas volume in the tank cells), results in a greater increase in pressure than at the lower end of the curve. In consequence this type of tank has limitations in scope for use at high pressures. To meet these conditions a type of tank containing cells which are pre-pressured has been introduced, and is now freely used as an alternative to, or in conjunction with, normal type tanks.

The pre-pressured tank differs from the normal type tank by the elements or cells being filled with gas at a pressure higher than atmospheric, although they are constrained to occupy the same volume when assembled. This results in a different pressure-volume characteristic which is shown in the upper curve; thus for a given increase in pressure a larger volume of oil V' can be accommodated at a high pressure than in the case of the normal tank. On the other hand, this type of tank cannot, of course, be used for lower pressures than that at which the cells are assembled. The use of pre-pressured tanks has also the advantage that higher pressures may be maintained in the cable, thus permitting longer lengths to be fed.

To illustrate the comparative effect of static and transient pressures on the hydraulic design it is interesting to consider two extreme profile conditions which might occur, i.e. the case of a cable having a horizontal profile, and that of a vertical profile. Fig. 3 shows alternative methods of feeding a cable with a horizontal profile, and the corresponding pressure tank distribution.

The total gas volume of the pressure tanks required is determined by the total oil expansion of the cable and the maximum static pressure permissible which is the same in each of the cases shown; but it will be seen that the *distribution* of tanks on the cable route is determined solely by transient pressure conditions. Thus the distribution of tanks can be varied from the provision of a few large tanks spaced at long intervals to that of a larger number of smaller tanks at more frequent intervals. Theoretically there is no need to subdivide the cable into sections by means of stop joints, although in practice it is customary to do so to provide some segregation in the event of damage causing oil leakage. It will be seen also that on going to the limit, the cable itself might contain its own continuous pressure tank or other means of accommodating oil expansion.

Fig. 4 illustrates the case of a vertical cable; in this case it will be seen that transient pressures are of small magnitude compared with static pressures, and that it is necessary to subdivide

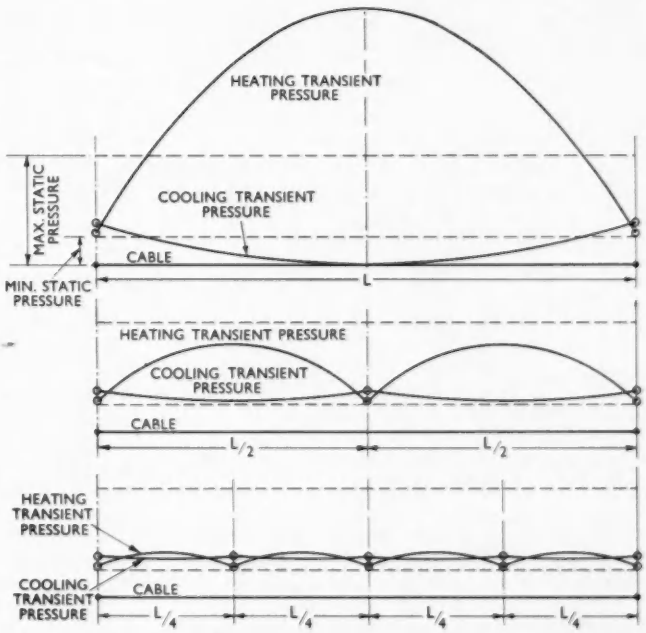


Fig. 3.—Distribution of oil pressures in a horizontal cable profile with alternative distribution of pressure tanks.

the line at intervals with stop joints in order to limit the maximum hydrostatic head.

The foregoing typifies the problems that have to be considered in planning the feeding arrangements for an oil-filled cable installation. In most cases the profile to be considered is undulating and advantage is taken of the natural configuration of the route in positioning the tanks.

GAS GENERATION.

The first 132 kV cable installed was commissioned late in 1931. A few weeks later it was found on making a routine inspection that certain of the gravity type feed tanks had become distended. An examination showed that they contained hydrogen gas at a fairly high pressure and that the oil duct of the adjacent cable also

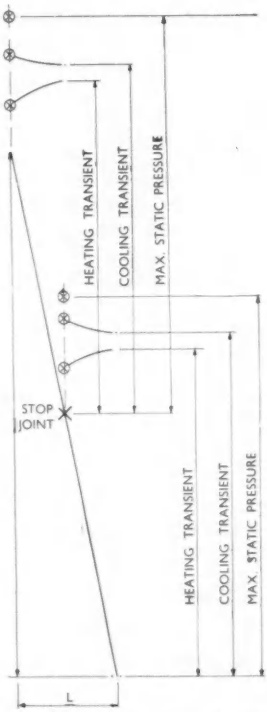


Fig. 4.—Distribution of oil pressures in a vertical cable.

contained hydrogen. This was the first indication of a condition which had not been experienced in any previous oil-filled cable installation.

A series of investigations was carried out on the section of the cable concerned which involved reimpregnating the cable in the ground, breaking down and examining the joints, and electrically testing the cable and joints. The only abnormality disclosed by these investigations was that one of the straight joint sleeves was found to contain gas under pressure instead of being filled with oil.

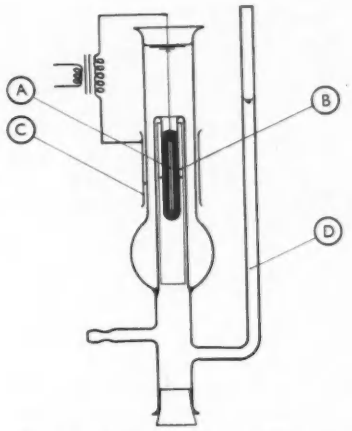


Fig. 5.—Apparatus for testing gas absorption or generation in oil.

It was not long before further cases of gas generation occurred at other points on the route, and in every case the same abnormality was found to be present in a joint. It was also found that all the joints concerned were situated at low pressure areas in the cable system, the oil-pressure being below 15 metres head of oil or approximately 18 lb./sq. in.

This phenomenon led to a considerable investigation into the behaviour of oils under stress, which showed that for any type of oil at a given pressure, there is a critical electrical stress above which gas would be generated, due to ionic bombardment within any bubbles or voids enclosed by the oil. At a little below this critical stress, any free gas would either be absorbed by electrically stimulated chemical reactions with the oil, or would remain indefinitely more or less in equilibrium with it, depending on the chemical characteristics of the oil. Highly refined oils, i.e. those consisting largely of 'saturated' hydrocarbons, would not *absorb* gas at any stress, but at the stresses existing in the dielectric of these cables, might *generate* gas unless the hydrostatic pressure was above a certain value.

A very simple apparatus was devised by Emanueli to demonstrate the behaviour of oils towards gases under stress, and in its modern form is

shown in fig. 5. This apparatus consists of an annular chamber *B* in which the oil and a selected gas is submitted to stress between the inner mercury electrode *A*, and the outer metal foil electrode *C*. The change in the volume of the gas according to whether there is generation or absorption by the oil is shown by the alteration of oil level in the side tube *D*.

By means of the apparatus described it was possible to establish the degree to which an oil could be refined without destroying its ability to absorb gas under the conditions of electrical stress existing in the cables, and furthermore, to determine what proportion of an oil-soluble hydrocarbon containing ' unsaturated' or ' aromatic ' groups, should be added to refined oil to confer gas absorbing properties.

The use of this apparatus has since enabled the manufacturer to check the stability of oils before their use, so that a precise specification can be drawn up to ensure that any type of oil used will suit exactly the conditions under which it will have to operate.

The oil used for the cables installed up to the time of this investigation was definitely in the ' highly refined ' category, liable to generate gas if air should be present in a highly stressed zone of the impregnated dielectric. As a remedy it was proposed to eliminate the gassing tendency by replacing the free oil in the cable duct with a strong solution of pure naphthalene in a less highly refined oil, naphthalene having a great capacity for absorbing hydrogen gas under stress on account of the essentially ' aromatic ' structure of its molecule.

In practice this was done by pumping the new naphthalene-oil mixture in at one end of each oil section and allowing the original oil to flow out at the other end, until the central duct of the cable contained the desired proportion of the new mixture. The normal temperature changes in the cable during its subsequent operation were found to be sufficient for diffusing the mixture into the dielectric. In many cases these oil changing operations were carried out while the cables were in normal commercial operation.

As it was found that the initial gas bubbles necessary to initiate gas evolution were trapped during jointing operations, it was also decided to re-impregnate all joints below a pressure of 18 lb./sq. in. with the replacement naphthalene-oil mixture.

These operations were carried out on all the original 132 kV installations and on some of the 66 kV cables, although in the case of the latter, gassing troubles were much less in evidence due to lower stress gradients. As all the cables treated are still operating satisfactorily, it can safely be assumed that the cure was effective. In fact, a length of 132 kV cable was removed from one of the affected routes in 1946 and its

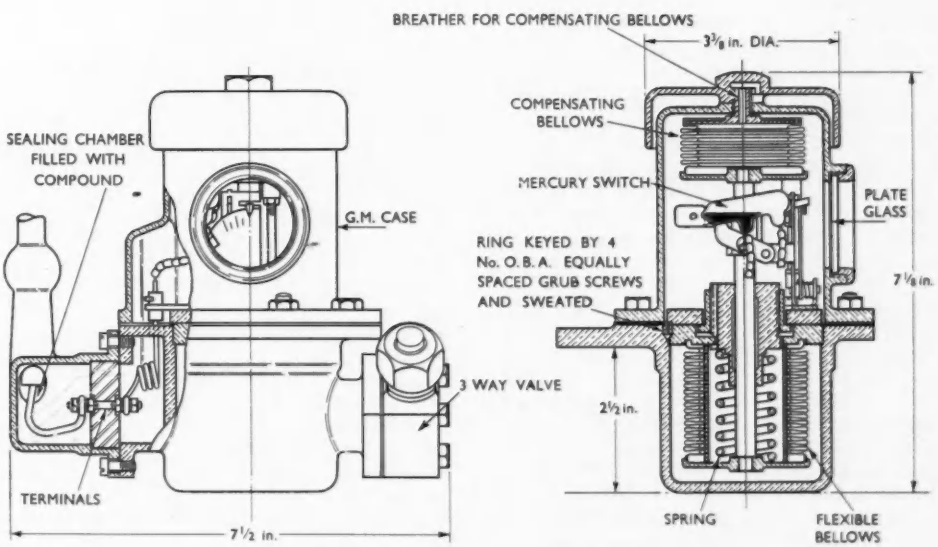


Fig. 6.—Latest pattern low oil pressure indicating switch.

condition was very carefully checked. Dielectric power factor and high voltage tests indicated that the cable was in as good a condition as when first installed, there being no indication whatever of dielectric deterioration.

OIL LEAKAGE INDICATION AND LOCALISATION.

In view of the importance of cables of this type in the supply system of which they form a part, it is often considered justifiable to install

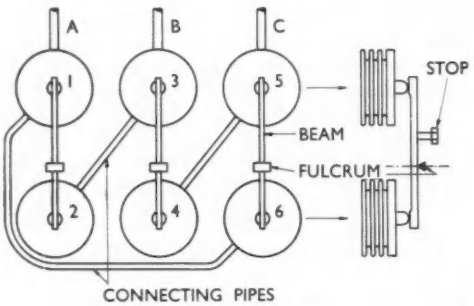


Fig. 7.—Three-phase differential oil pressure indicating switch.

apparatus to detect oil leakage which may very occasionally occur due to mechanical damage or other causes. Various devices have therefore been developed to indicate loss of oil and to localise the section of cable in which it may occur.

These devices have been designed to operate at a definite low oil-pressure or alternatively by a comparison of pressures. The first condition is covered by the use of a low oil pressure indicating switch (L.O.P.I.).

The latest design of this type of switch is shown in fg. 6. It consists of a spring-loaded flexible bellows which is normally compressed by external oil pressure, the oil container being connected to the oil system of the cable. On lowering the oil pressure to a predetermined value, the mercury switch is tripped and actuates a signal. An interesting feature of this switch is the use of a compensating bellows shown above the mercury switch, which cancels out any effect on the calibration due to temperature changes in the air contained in the switch casing, the latter being sealed against the ingress of external air or moisture.

An alternative to the L.O.P.I. switch is the use of a contact type pressure gauge, and in a number of installations this form of alarm has been used.

A brief consideration of the pressure conditions in the cable under varying loads shows that a switch operating at a definite pressure must necessarily be arranged to operate below the minimum operating pressure in the cable even if a leak should occur while the cable is loaded.

It is desirable therefore to have some form of alarm device which will take account of load variation. This has been achieved by the development of switches operating on the differential principle which compare oil pressures in different phases or sections of the cable.

In the case of a feeder consisting of three single-core cables separately fed, all three phases should of course behave in the same way under all conditions of load. The fundamentals of a switch of this type which compares the oil pressures in the three phases are shown in fig. 7. This device operates at a specified difference in pressure between phases, e.g. it may be set to operate at, say, 20 per cent drop of pressure in one phase. The switch consists of three pairs of bellows, connected as shown and with each pair of bellows loading opposite ends of a biased beam, the fulcrum of the beam being adjustable to vary the percentage pressure difference. The unbalancing of the beam, due to loss of pressure in one bellows, causes a mercury switch to trip.

Fig 8 shows the switch in its final form. The development of this device took place in 1935. It was adapted from an earlier American design which achieved the differential operation by the use of pairs of bellows in opposition, but having different diameters, which did not permit of adjustment to the bias.

The pressure-operated devices so far described are not suitable for installations employing gravity type feed tanks. To meet this need, a switch known as the Low Volume Indicating Switch has been used to a limited extent. In this case the feed tank itself is mounted on a cradle pivoted on knife edges at one end and supported by springs at the other, the device in fact constituting a type of spring balance. Loss of weight in the tank operates a simple mechanism tripping a mercury switch.

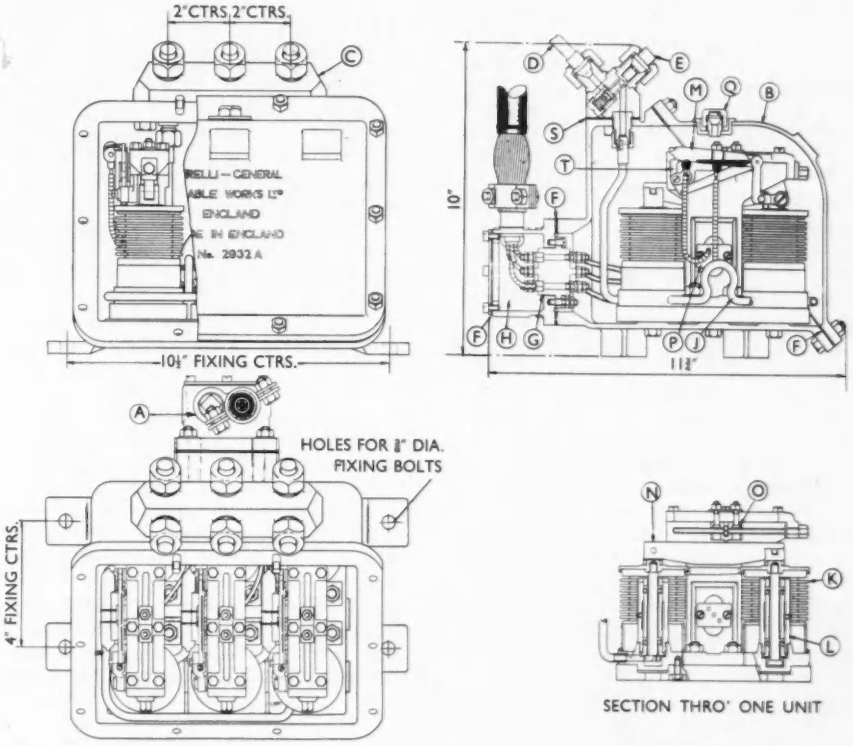
The transmission of the alarm signal to the cable termination is a fairly simple operation, and a typical circuit is shown in fg. 9. In this case the alarm switches are connected to pilot wires, and the location of the tripped switch is effected by the use of a Murray loop test. This circuit employs a continuous circulating current in the pilot wires and gives an indication of failure of this current either by reason of an open circuit or mains supply failure. It will be appreciated that the localiser will only indicate

the position of the particular switch which has operated ; the method of finding the actual point of leakage is another matter.

It should be emphasised that the devices described do not constitute ' protective devices ' in the normally accepted sense of the word. Their operation does not normally require the cable to be taken out of commission, and unless the rate of oil leakage is extraordinarily high, cables can be maintained in commission indefinitely, provided the loss of oil is made good.

Opinion has been divided on the necessity of the installation of alarm devices at all, and there are many miles of oil-filled cables in operation in which reliance is placed on periodical inspection of pressures.

The precise location of an oil leak in an oil-filled cable is at first sight a comparatively simple matter, involving the measurement of leakage flows and using methods analogous to electrical fault finding. A serious complication arises, however, which does not occur in similar electrical tests. It is that, owing to continuous changes in ground temperature, there is normally



ITEM	DESCRIPTION
A	DETACHABLE TERMINAL BOX (WITH VARIABLE CABLE ENTRY POSITIONS)
B	GUN METAL CASE
C	VALVE BLOCK
D	OIL CONNECTION TO CABLES
E	CONNECTION FOR TESTING PURPOSES
F	M/C FACE WITH NEOPRENE CORK GASKET JOINT
G	BAKELITE TERMINAL BLOCK
H	COMPOUND FILLED

ITEM	DESCRIPTION
J	INTER-CONNECTING PIPES
K	FLEXIBLE BELLOWS
L	BALL BEARING GUIDE
M	MERCURY SWITCH
N	ROCKER BEAM
O	VARIABLE PERCENTAGE PIVOT BLOCK
P	PAXOLIN GUIDE FOR LEADS
Q	PRESSURE TESTING UNION

Fig. 8.—Three-phase differential oil pressure indicating switch.

a flow of oil into or out of the cable. This may be of such dimensions as to cause a flow equal to, or even greater than, the leak itself.

The pressure conditions obtaining in a cable containing a leak are shown in fig. 10, which also illustrates the principle on which a localisation method using a loop test is based.

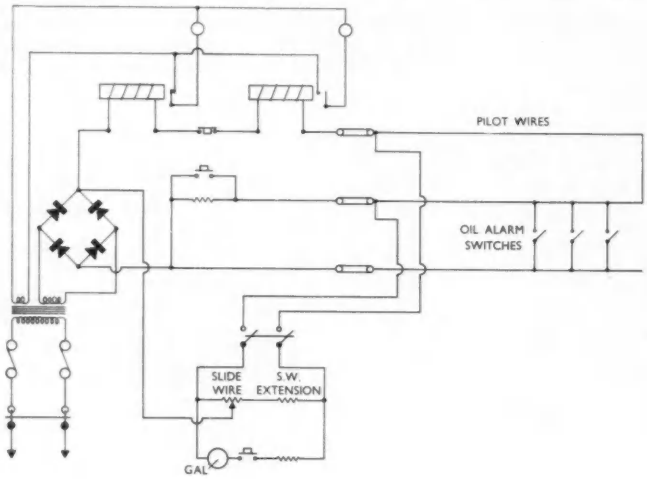


Fig. 9.—Typical alarm circuit.

This particular test is applied normally to a feeder consisting of three single cores. In this diagram, the continuous line shows the pressure gradients due to the leak, and the broken line those due to oil absorption owing to temperature change in the cable. The two lengths L of cable represent two single cables looped together at one end, with the two sight-tubes of the oil leak localising set at the other, the position of the leak being at a distance X from the loop. The diagram shows the two phases in what may be described as an "unfolded" condition. In practice, of course, the two sight tubes are side by side at the top ends of the two phases, and the centre of the loop is at the end.

In carrying out the test, the leaking cable and one sound cable are looped at the end remote from the testing point; the third cable is used for temperature correction. Considering only the pressure gradient due to leakage, it will be seen that if the oil pressures at each side of the loop are maintained at the same value, the pressure drop to the point of leakage will be the same. As under these conditions the rate of flow is proportional to the frictional resistance of the cable, which in turn is proportional to the length, it will be seen that the ratio of the oil flows into both sides of the loop will be the inverse of the ratio of the lengths of cable between the testing point and the point of leakage. In carrying out this test the gross volumes of oil flowing into or out of each of the two looped cores are measured over a definite time, and a correction for flow due to temperature change is applied by subtracting from, or adding to these readings, the oil volume flowing in or out of the sound core, it being assumed that all three cores are equally affected by temperature.

Fig. 11 shows an apparatus devised for carrying out this test. It consists of three glass sight tubes, each of which is connected to one single-core cable. All other feeds being disconnected, the oil in these tubes is kept at exactly the same level by manipulating three screwed pistons which enter cylinders and which are calibrated with micrometer scales, thus during the test, oil volumes entering or leaving the three single-core cables are measured on the micrometers. This method of location has proved successful under favourable conditions. It has, however, been found that due to temperature differences between the individual cores and other disturbing causes, results are often approximate.

The location of an oil leak is more difficult in the case of a 3-core cable. A trial-and-error method which is often used when only one cable is available, is to effect a temporary

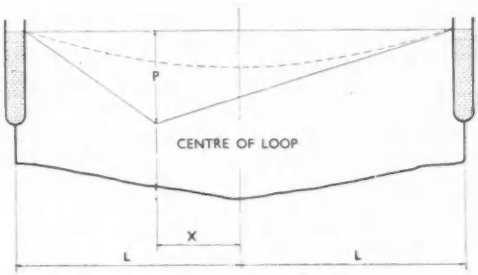


Fig. 10.—Principle of oil leak localising test.

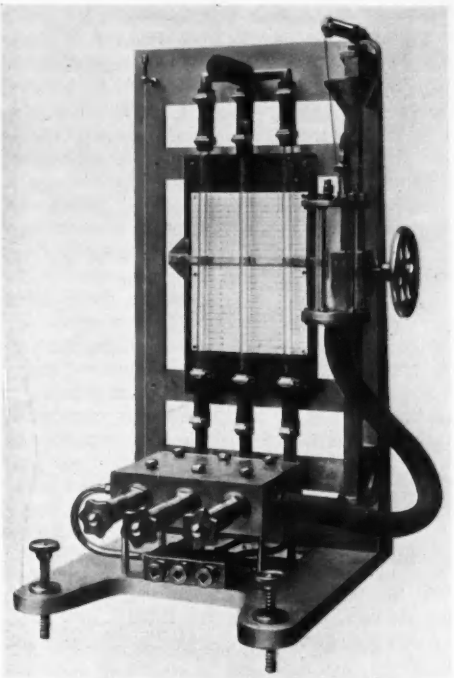


Fig. 11.—Instrument for oil leak localising test.

stoppage of the oil duct and observe on which side of the stoppage leakage is occurring.

In the case of a 3-core cable, this can conveniently be done by temporarily closing the oil communication at a joint and by taking observations of oil flow on both sides. In this way the leakage can be located to a given drum length of cable. To locate the leak within this length, or to locate a leak in a hollow-core cable, where it is not possible to block the oil duct mechanically, a technique has been developed to create the stoppage by freezing the cable solid by the use of liquid oxygen. Observations are then made to find the direction of the leakage flow.

Fig. 12 shows a 'freeze' being carried out. The method adopted is to place a temporary sleeve around the cable into which liquid oxygen or nitrogen is poured until the oil in the cable is frozen. The freezing point of the cable is approximately −50 deg. C. and the temperature of liquid oxygen −183 deg. C. Freezing does not take long, and the time varies from 15 to 30 minutes on various types of cable. The cable can be maintained in its frozen state as long as desired by continuing to replace the evaporating oxygen, and the time taken to thaw out is about 2 to 3 hours. It should be emphasised that the freezing process has no detrimental effect on the cable, provided that no movement is allowed to take place when in its frozen condition, and it is perhaps unnecessary to add that the cable should be kept out of commission until normal temperatures have been reached.

One of the reasons for the development of the various methods of leak location described above was the occasional occurrence of defective longitudinal seams in the lead sheaths of some of the earlier cables. The development of lead extrusion machines which produce seamless lead sheathing has largely eliminated lead defects of this type.

WARTIME MAINTENANCE EXPERIENCES.

During the last war quite a number of important cable routes were damaged by bombing——in many cases direct hits were experienced on oil-filled cable routes. In the London area alone between forty and fifty cases occurred.

A direct hit on a cable route very often meant that the cables were completely severed and it was not an uncommon experience to find the bomb crater full of water from damaged mains, pervaded with leaking gas, with oil freely draining from the severed cable ends. In several cases cables were completely drained of their free oil. In spite of these difficulties the cables were evacuated and reimpregnated in the ground,

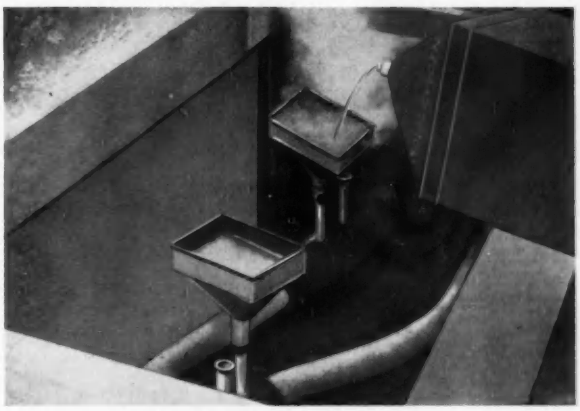


Fig. 12.—Freezing cables by liquid oxygen.

it being normally necessary to insert only a very short length of cable to repair the damage.

CABLES AND ACCESSORIES.

During the period under review considerable developments have taken place in the design of cables, joints and accessories.

In the case of cable design, a considerable increase in maximum dielectric stress value has taken place since the earlier period, for example in the case of the original 132 kV cables, the maximum design stress was 75 kV per cm. A figure of 90 kV per cm. has been used on recent designs. A cable which will operate at 301 kV and which has been installed in Canada has a maximum stress of well over 100 kV per cm.

The thinner dielectric wall, of course, effects considerable economies in the construction of the cable itself, and there is consequently some economy in the sizes of oil feeding tanks required due to the smaller oil expansion to be accommodated.

Further economies have been effected by the simplification of the outer protection of the cable. Most oil-filled cables manufactured between 1930 and 1937 were provided with two lead sheaths, the inner sheath being the oil-retaining sheath which is reinforced against internal oil pressure with metal reinforcing tapes, the outer sheath forming a protective covering. Present-day cables normally have only one lead sheath, the pressure reinforcing tapes being protected by rubber or similar material which effectively prevents any corrosive action from the soil in which the cable may be laid.

To indicate the measure of economy obtained by the omission of the outer lead sheathing and the reduction of dielectric thickness, it is sufficient to say that the weight of lead in a 1930 type of 0·20 sq. in. 132 kV cable was approximately 12½ tons/1000 yards against the present-day figure of approximately 4¼ tons/1000 yards.

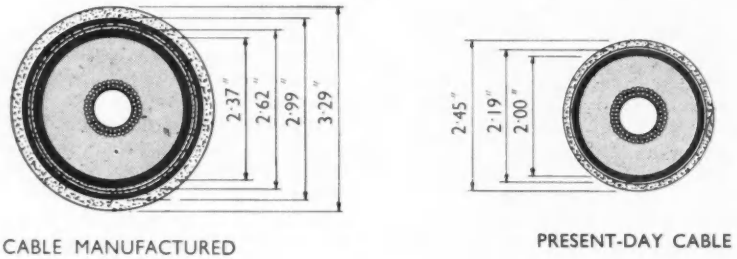


Fig. 13.—Comparison of 1930 single-core 132 kV, oil-filled cable with similar cable of present-day manufacture.

Fig. 13 shows side by side a 132 kV cable of 1930 manufacture, and one of present-day construction, and illustrates these changes.

Maximum permissible conductor temperatures

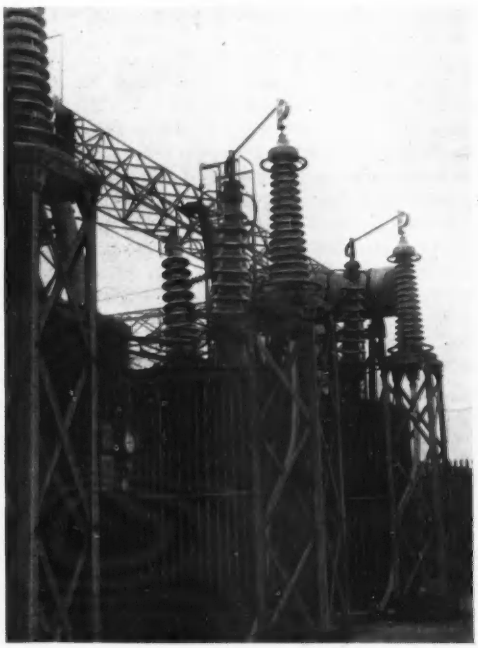


Fig. 14.—Outdoor type sealing ends.

have also been raised, the present figure being 85 deg. C. compared with 75 deg. C. 24 years ago, and in at least one case a maximum temperature of 100 deg. C. has been permitted for an occasional short time peak load period.

Further interesting developments in cable design have taken place, amongst which is single-core cable having the oil-ducts formed in the sheath. This cable, known as the ' fluted lead ' type, is principally used for comparatively short lengths of single-core tails terminating 3-core cables. By its use the design of trifurcating joints is considerably simplified.

A 3-core cable having leakage indicator wires enclosed inside the main cable has been used.

Another type of construction has been the use of a 3-core cable of S/L type. This consists of the three single hollow-core cables separately lead sheathed and enclosed in one outer armouring.

To improve the thermal characteristics of 3-core cable, copper instead of steel spiral oil ducts have sometimes been employed.

The range of sizes of conductor used has varied from 0·1 sq. in. to 1·5 sq. in. in single-core cable and from 0·1 sq. in. to 0·6 sq. in. in 3-core construction.

A very recent development in cable design has been the introduction of an oil of lower viscosity than the original type, which has the effect of reducing frictional losses in the oil ducts, thus reducing transient pressures.

The type of paper used in the dielectric wall has been improved by advanced technique in paper manufacture, and much consideration has been given to paper lapping operations to ensure precision of registration of papers and the control of tension.

A further recent development in oil-filled cable practice has been the use of aluminium sheathing. In the case of a 3-core cable this effects considerable economies as a result of the strength and rigidity of the aluminium sheath as compared with lead sheath. Thus a cable of this type need not be provided with external reinforcing tapes and also the use of spiral oil ducts is not necessary. An aluminium sheathed 33 kV oil-filled cable has recently been laid in this country and further installations will shortly be carried out.

Many detailed improvements have been made in the design of joints and accessories which would be too lengthy to describe in detail. One development of great practical importance, however, that should be mentioned is the increasing use of oil immersed sealing ends, which enable cables to be connected directly into transformers or switchgear.

Before the development of this termination it had been normal practice to provide outdoor type sealing ends for the cables and external porcelain bushings in the apparatus to which it was connected. A typical arrangement of this type with 132 kV cables is shown in fig. 14.

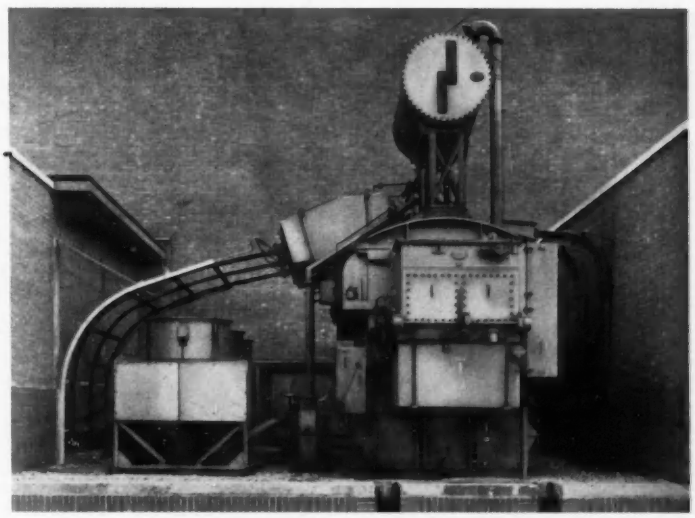


Fig. 15.—Switchgear type sealing ends terminating into a transformer.

With the co-operation of transformer and switchgear manufacturers, oil immersed sealing ends have been used increasingly during the last few years, effecting considerable economies in the combined installation and at the same time providing the advantages of totally enclosed connections.

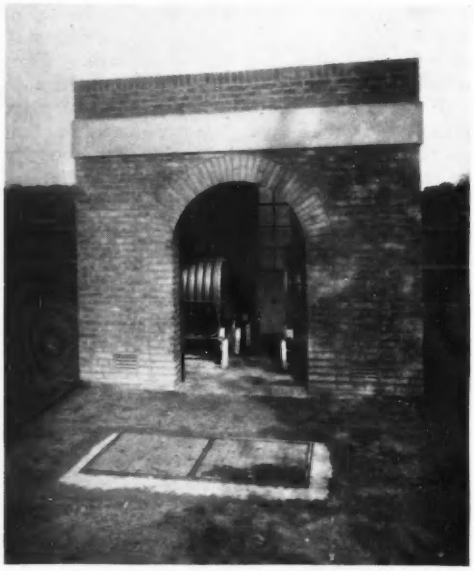


Fig. 16.—Feed tank building.

Fig. 15 shows an installation of 132 kV sealing ends of this type.

INSTALLATION PRACTICE.

Installation practice has undergone certain changes during the period under review.

The reduction in weight and diameter of cable facilitates the laying of longer lengths and these are frequently laid by the use of a power winch which is connected to the cable through a mechanical pulling grip or eye, by means of which the pulling tension is mainly carried by the cable conductors. A considerable saving in manpower results from this practice.

As mentioned previously, when feed tanks of the 'gravity' type were used it was often necessary to provide suitable accommodation to house them at the required physical head above ground level. To achieve this it was sometimes convenient to make use of existing buildings at the terminations of the cable, but in one or two cases quite high and costly structures had to be specially built. By taking advantage of the high points on undulating cable profiles, however, a comparatively low elevation was often found adequate which could be provided in buildings of small dimensions. In fact, in many cases on a rapidly falling profile, feed tanks were accommodated underground in concrete chambers.

Fig. 16 shows a building containing feeding tanks of this type. This was constructed at the crest of a rise with ground falling away on both sides; the feed tanks are visible. In the foreground there is a manhole giving access to a concrete pit containing the cable joints.

With the present system of oil feeding, using pressure tanks only, the need for physical head has ceased to exist, and very much simpler and cheaper means of accommodation are employed.

Where a large number of tanks and joints have to be accommodated at one point, underground concrete chambers are used occasionally. Normal present-day practice, however, is to accommodate the pressure tanks in separate individual concrete tubes buried direct in the ground. These can be provided with manhole covers

Fig. 17.—Modern joint installation showing buried pressure tanks.

Fig. 18.—Installation of 132 kV cables at Inchinnan.

to give access to the tanks for inspection purposes, or they can be buried completely. In the latter case it is desirable to provide access to the oil system of the cable by means of pipe connections brought into shallow manholes or surface inspection boxes, so that inspection of oil pressures can be carried out periodically. These manholes may also be used to accommodate oil pressure alarm switches.

Fig. 17 shows a tank installation of this type on a 33 kV cable route.

The majority of oil-filled cables laid in this country have been buried direct in the ground in accordance with normal British practice. Occasions, however, have arisen where special methods of installation have had to be adopted. Details of some of these installations, together with installations having other interesting features, are given in the following brief survey.

132 kV Submarine Cables at Inchinnan.

During the war about $1\frac{1}{4}$ miles of 132 kV overhead Grid line in the south-west Scotland area were replaced by a 132 kV underground oil-filled cable.

This involved the crossing of two rivers,

Fig. 19.—Crossing of River Orwell at Ipswich.

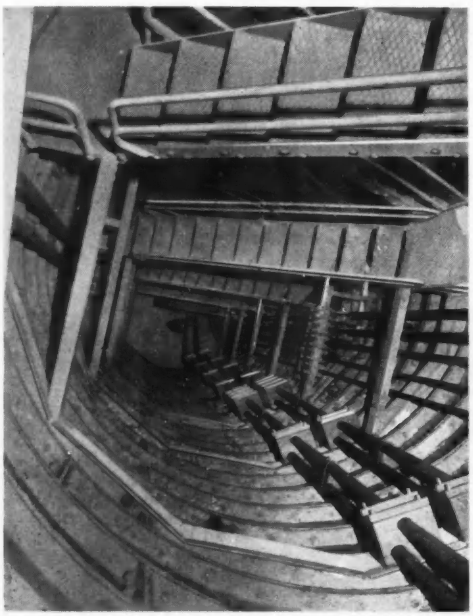


Fig. 20.—132 kV and auxiliary cables in one of the shafts in Shoreham Harbour Tunnel.

namely the Black and White Carts, both tributaries of the River Clyde. The crossing of the Black Cart was carried out by dredging a trench in the bed of the river and by laying the cable from drums mounted on floats. The cable was 132 kV single-core, 0·3 sq. in. cross-section, armoured, with a single layer of cadmium copper wire. The three single-core phases were laid simultaneously, being bound together as they were laid into the bed of the stream. A view of the installation in progress is shown in fig. 18.

As the White Cart is a much shallower stream at the point of crossing the cables were pulled across the stream at low tide, supported temporarily on a timber structure, and were then buried in a trench dug by hand during the low tide periods.

Crossing of the River Orwell, Ipswich.

This crossing was carried out during the installation of 33 kV oil-filled cables for the Ipswich Corporation in 1946.

It was necessary to lay a cable in the bed of the River Orwell immediately across the face of the main lock gates at the entrance to Ipswich Harbour, the crossing also being continued across the "New Cut", another branch of the Orwell. The cables were laid direct in the bed of the river in dredged trenches and were protected by concrete bags. A special construction was adopted to lead the cable up the vertical wall at the quayside, the cables being cleated in a vertical concrete chase and protected with concrete slabs. Fig. 19 shows the laying operation in progress.

Fig. 21.—Cable bridge over Regents Canal, Brunswick Wharf, Islington.

River Liffey Tunnel, Dublin.

The installation of cables under the River Liffey in Dublin consisted of two 3-core, 40 kV, 0·25 sq. in. cables and was carried out by the Electricity Supply Board. These cables were armoured with one layer of steel wire and were installed in a tunnel with vertical shafts approximately 85 feet deep on the east side and 81·6 feet on the west side, the horizontal portion of the tunnel being 376 yards long.

In the shafts the cables were suspended in mining type cleats.

Shoreham Harbour Tunnel.

This is a more recent installation comprising two 132 kV feeders, consisting of two trefoil groups of single-core, 0·3 sq. in., single steel-armoured cables. The tunnel provides the exit for cables from the new Brighton 'B' Power Station and is constructed under the bed of the harbour at Shoreham. The two tunnel shafts are vertical, being 86 ft. deep on the south side and 100 ft. deep on the north side, the width being 175 ft., the tunnel being constructed at an incline. Fig. 20 shows the arrangement of the 132 kV and auxiliary cables in one of the tunnel shafts.

Brunswick Wharf, Islington.

A large 132 kV oil-filled cable installation was recently carried out connecting Brunswick Wharf Generating Station at Poplar and the B.E.A. distribution centre at Islington. The route of this cable presented many difficult civil engineering problems which were successfully overcome. The cables were normally laid direct in the ground in trenches, but tunnels were driven under some of London's busiest main roads : for instance, East India Dock Road, Hackney Road and Bow Road. A special cable bridge was designed and erected to carry the cables over the Regents Canal as shown in fig. 21. Two feeders were laid in the same trench, each being capable of transmitting a continuous load of 120 MVA. The cross-sections vary from 0·5 sq. in. to 0·75 sq. in. to suit the various laying conditions encountered.

Fig. 22.—33 kV oil-filled cables laid in asbestos cement tubing for British Transport Commission.

British Transport Commission.

For the frequency changeover which is now being carried out in connection with the Southern Region Suburban Area electrification scheme, approximately 285 miles of oil-filled cables are being installed. The majority consist of 3-core 33 kV cables with a small amount of 3-core 66 kV cables and will replace the existing 11 kV distribution system.

The cables are being laid in precast concrete troughing protected with lids which are normally at ground level. Where this construction cannot be used, for instance over bridges and in other difficult conditions, the cables are laid in asbes-

tos cement tubes mounted above ground level. Fig. 22 shows a run of the latter type of construction adjacent to the railway track.

301 kV Installation for the Aluminum Company of Canada.

A very interesting installation has just been completed at the Hydro-electric Power Station at Kemano in British Columbia for the Aluminum Company of Canada, Limited, which is the principal fully owned subsidiary of Aluminium Limited. The installation concerns an oil-filled cable which will operate at 301 kV and which forms the termination into the power station of the transmission line between Kemano and the Aluminum Smelting Works at Kitimat. The cable consists of a 3-phase feeder made up of single, hollow core phases and is believed to be the highest voltage cable to be put into operation in the North American continent.

The cable has been laid in wood cleats in a cable tunnel between the underground power station and the switchyard at which the transmission lines terminate. When in commission the cable will carry the output of two generators, i.e. a total of 213 MVA, its maximum continuous rating being 287 MVA. Fig. 23 shows an outdoor sealing end constructed for this installation.

Fig. 23.—301 kV outdoor sealing end.

275 kV Installation at Staythorpe.

A further installation of oil-filled cable has recently been put into commission at the High Voltage Cable Testing Station at Staythorpe established by the B.E.A. In this case the cable is built for 275 kV and is installed with other types of high voltage cable.

Acknowledgment.

The author wishes to make acknowledgment to the various Authorities referred to for permission to publish the information relating to the installations mentioned.

New Semiconductors

By R. W. DOUGLAS, B.Sc., F.Inst.P., F.S.G.T., and C. H. L. GOODMAN, M.A., B.Sc.
G.E.C. Research Laboratories

The present article indicates the requirements to be met in the search for new semiconducting materials suitable for use in crystal valves. The importance of a combination of high charge-carrier mobility and relatively high energy gap suggests that a covalent-ionic type of bonding is required. "Substituted diamond" type structures are the simplest having such bonding, and the relationships between charge-carrier mobility, energy gap and bond-type are discussed for them. Some new ternary diamond-type compounds are described.

INTRODUCTION.

OF recent years ever-increasing attention has been paid to the peculiar physical properties of semiconducting materials. Many devices employing them are of great technical interest, for example crystal valve amplifiers and photo-conductive detectors of X-rays, and infra-red and ultra-violet radiation. It is striking, however, how few basic materials are employed in these devices, scarcely a dozen all told, and yet a very long list could be made of substances known to have shown properties characteristic of a semiconductor, such as very large thermo-electric power, rectification of alternating current, or photoconductivity. Even then there can be little doubt that such a list would name but a fraction of the vast number of semiconducting materials yet to be discovered. It is inviting to speculate, therefore, that there must exist materials with such properties that they could replace those at present in use with advantage both to device performance and cost. The problem is how to find them, for present knowledge of the subject is not great. This article is chiefly devoted to considerations arising from a systematic investigation carried out with the aim of increasing understanding of factors affecting electrical properties of importance for crystal valves. Attention has been restricted to a single group of crystals in the interests of simplicity, but the theoretical concepts and general line of approach are capable of more general application.

SOME PROPERTIES OF SEMICONDUCTORS.

Three parameters are of primary importance in describing a semiconductor: the energy gap and the mobilities of both types of charge carrier (electrons and positive holes). The energy gap is the activation energy to enable carriers to reach the conducting state, and in fact a material can be defined as a semiconductor if such an activation, either thermal or optical, is found. In a perfectly pure defect-free crystal of a material the electrical conductivity is determined by the number of activated charge carriers, and by their mobility. Such a material is said to be an intrinsic semiconductor, and its conductivity varies with temperature as $e^{\frac{-E}{2}kT}$ where E is the energy gap measured in electron volts. Thus conductivity increases markedly with rise in temperature. (This description implies that mobility does not vary with temperature, and in fact its variation is usually small compared with the changes in carrier concentration). In practice, crystals have imperfections and usually impurities present in them which can furnish charge carriers independently of the above mechanism, swamping in numbers the activated carriers at room temperature if the energy gap is greater than about $\frac{1}{3}$ eV. Such a material is referred to as an extrinsic or impurity semiconductor. Impurities can give rise either to an excess or a deficit of electrons in the semiconductor. Materials with an excess of electrons are termed N-type (negative) and with a deficit

P-type (positive). P-type materials appear to conduct as if the current were carried by a positively charged carrier; these are the positive holes referred to earlier. In certain circumstances, particularly important for the operation of crystal valves, N-type material can transmit small concentrations of positive holes, and P-type material of electrons. These charge carriers of opposite sign to that characteristic for the particular specimen are termed the minority carriers. The average time for which minority carriers can exist in a given specimen of a material before combining with the majority carriers is known as the lifetime of that specimen. This parameter is of great importance for the preparation of amplifying devices; however it can be measured only with very highly purified specimens. As the order of purity required is far greater than that so far obtained with nearly all the materials mentioned here, further consideration of lifetime has been neglected.

The energy gap determines the carrier concentration in an intrinsic semiconductor, and this and the carrier mobilities determine the conductivity. Carrier mobilities are usually quoted in terms of velocity for a given applied potential, i.e. cm/sec for 1 volt/cm or $cm^2\ V^{-1}\ sec^{-1}$. Mobilities can vary very widely, thus the electronic mobility in InSb is ca. 50,000 $cm^2\ V^{-1}\ sec^{-1}$ while in CdTe it is ca. 300 $cm^2\ V^{-1}\ sec^{-1}$, both at room temperature. Mobilities increase as temperature falls. This point will be discussed below.

A SPECIFICATION.

It is advisable before searching for a semiconductor for a particular application to draw up a specification of the properties desired. For a material for use in crystal valves this could be written :

(*a*) Energy Gap.

This should be sufficiently high to ensure that the material does not show appreciable intrinsic conductivity at operating temperatures, which would indicate a gap greater than 0·8 eV. In this connection it should be noted that germanium with an energy gap of 0·76 eV cannot be used in crystal valves above about 70 deg. C.

(*b*) Carrier Mobilities.

In crystal valve operation the mobility of the minority carrier should be as great as possible in order to cut down transit-time effects. A mobility value in excess of 1,000 $cm^2\ V^{-1}\ sec^{-1}$ is desirable unless low frequency operation is all that is required. Furthermore, for point-contact triodes the ratio of mobilities of electrons and holes should be large.

(*c*) Dielectric Constant.

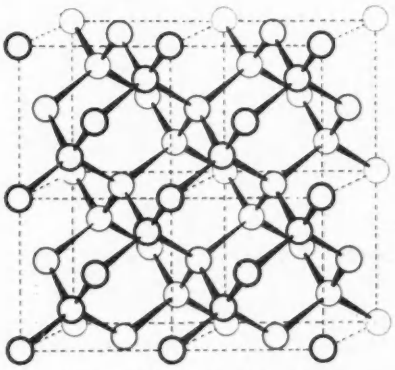
This should be large, of the order of 10 or more. Values very much lower would result in the ionisation of impurity atoms being incomplete at normal operating temperatures, so that the conductivity of the material would change appreciably even though the intrinsic range was not reached.

(*d*) Thermal Capacity.

This should be large, of the order of 0·1 cal. $cm^{-1}\ sec^{-1}\ deg^{-1}$ to ensure adequate heat dissipation from the body of the material.

CHOICE OF CRYSTAL TYPE.

In the specification just quoted the high carrier mobilities and dielectric constant required indicate that whatever material is chosen must have bonding which is appreciably covalent. Ionic bonds, with the large associated charges on the atoms of the crystal lattice tend to give very low carrier mobilities. This arises from the scattering of the charge carriers by interaction with the ions in the lattice, local charges upsetting the free movement of the carriers. Furthermore, ionic, unlike covalent, bonds are not readily polarisable, and hence have relatively small dielectric constants and refractive indices.



* Fig. 1.—The diamond structure.

Accordingly attention must be limited to materials showing a considerable degree of covalency.

A number of crystal structures is known which have appreciable covalency in the bonding, that is in which bonding electrons tend to be shared between the bound atoms and are not attached permanently to particular ions. Among

* The Structural diagrams shown in figs. 1, 2, 3 and 5 have been adapted from the drawings of A. F. Wells, "Structural Inorganic Chemistry," Oxford University Press, 1945.

these are diamond, wurtzite, marcasite, cadmium iodide and nickel arsenide types, to name several. The simplest of all these structures is diamond and in order to minimise complicating structure-dependent factors this was chosen for further investigation, particularly as two of the best-known semiconductors—silicon and germanium—crystallise in it. Work on other materials with diamond-type structure revealed, as had been predicted, a range of substances with wide variation in parameters, such as energy gap and carrier mobility, and this later knowledge can be used as a basis for predictions regarding other materials of similar structure.

TABLE 1.

Substance	Atomic Weight	Energy Gap	Melting Point	Electron Mobility	Hole Mobility
C	12·01	5·5	~3000	400	200
Si	28·06	1·12	1240	1200	250
Ge	72·60	0·76	940	3600	1700
α-Sn	118·70	0·06	?	⩾3000	?

THE DIAMOND STRUCTURE.

The diamond structure shown in fig. 1 is of the cubic type, and in it each atom is surrounded by four close neighbours which can be considered as arranged at the corners of a regular tetrahedron. Derived diamond structures with two or more types of atom in the lattice can be formed as will be described later, but the true diamond lattice contains only one atom type, and the bonding is essentially covalent. The tetrahedrally directed bonds are indicated by tapered lines in the diagram.

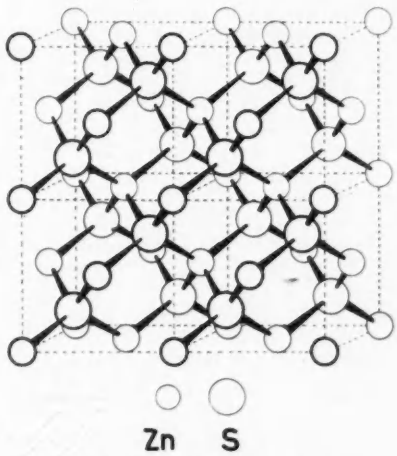


Fig. 2.—The sphalerite structure.

Only four substances crystallise in the diamond structure, all of them elements of Group IV of the Periodic Table : carbon (diamond itself), silicon, germanium and tin. Their main properties are given in Table 1 and are taken from the literature. Melting point and energy gap fall rapidly as atomic weight increases and the thermal conductivity behaves similarly[1]. The mobility, however, rises with increased atomic weight, as do the refractive index and dielectric constant. It is clear that for the true diamond structure some of the requirements in the specification are mutually exclusive.

SUBSTITUTED DIAMOND STRUCTURE.

(1) The Sphalerite Structure.

In some respects substituted diamond structures behave differently from the true diamond structure. The cause of this difference lies in the fact that the coexistence in the lattice of two or more different atom types results in a departure of the bonds from truly covalent type. This can be seen most easily in the simplest type of substituted diamond obtained by incorporating two different types of atom in the diamond lattice. This is the sphalerite, or zinc blende structure, shown in fig. 2. Each atom of the one type forms tetrahedrally directed bonds with four atoms of the other type. If these bonds were completely covalent, the two electrons in each bond would be equally associated with both the linked atoms, so that, as in the true diamond structure, each atom would effectively possess four electrons. Now the sphalerite structure is only found with compounds formed between Groups III and V, II and VI, and I and VII of the Periodic Table, that is between elements contributing 3 and 5, 2 and 6, or 1 and 7 valency electrons. Examples

are InSb, CdTe and CuBr. It is clear that in each case there is a total of eight valency electrons for each pair of atoms, but it is also clear that if these electrons are completely shared the atoms would acquire charges, becoming, for the examples above, In^{1-} Sb^{1+}, Cd^{2-} Te^{2+}, Cu^{3-} Br^{3+}. Now the attraction for electrons exerted by a neutral In atom is less than that exerted by a neutral Sb atom, while this difference in attractive power, or electronegativity is greater still between In^{1-} and Sb^{1+}. This attraction results in the electrons in the bonds in the lattice becoming more associated with the atom having the greater electronegativity, which process tends to reduce the apparent charges on both types of atom. Exactly the same argument holds for all sphalerite type compounds, the apparent charges on the atoms being greatly reduced. This matter has been dealt with elsewhere[2]. In effect, substances with the sphalerite or other substituted diamond structure have covalent bonds similar to those found in the true diamond structure, but with an additional ionic component of bonding, which increases the strength of the bonds and results in a higher melting point and energy gap for a given mean atomic weight than would be obtained if the bonding were purely covalent.

The reduction in the apparent charges on the atoms in the lattice, and the increase in bond strength, would both tend to favour high mobility. Neutralisation of the charges would eliminate the ionic scattering effect mentioned earlier, while bond strength is directly related to the amplitude of thermal vibrations, which upset the perfect periodicity in the positioning of the atoms in the lattice required for maximum mobility. If the amplitude of vibration is reduced the carrier mobility increases (thus mobility rises as temperature falls), and it is clear that an increase in bond strength effects just such a reduction. Thus it is to be expected in some cases, where the electronegativity factors are advantageous, that particularly high mobilities will be found. This is believed to be one reason for the high electron mobilities found with indium antimonide and mercury selenide ($\sim$50,000 and 10,000 $cm^2\,V^{-1}\,sec^{-1}$ respectively, at room temperature). This suggests the possibility that high mobility might in certain cases be found in a material of relatively high energy gap, one of the requirements of the specification. These arguments apply to any crystal structure, even the "ionic" sodium chloride structure as instanced by the lead sulphide group of compounds in which mobilities are comparable with those found in silicon.

To return to consider the sphalerite structure, some 20 compounds are known which crystallise in this lattice. Table 2 lists some of the more important properties of those compounds with energy gaps less than about 2 eV. This limitation has been made as materials with higher energy gaps cannot readily be made extrinsic semiconductors, either because impurity atoms are not readily taken into solid solution, or because the dielectric constant is too low for impurity atoms to become ionised at operating temperatures. The data listed are taken from the literature or from experiments carried out in these Laboratories. Mobility values given are the highest so far found.

TABLE 2.

Material	Melting Point (deg. C.)	Energy Gap (eV)	Electronic Mobility ($cm^2V^{-1}sec^{-1}$)	Hole Mobility ($cm^2V^{-1}sec^{-1}$)
AlSb	1060	1·6	100	$\sim$100
CdTe	1045	1·4	300	$\sim$100
GaAs	1250?	1·4	4,000	$>$200
InP	1150?	1·2	3,400	650
GaSb	702	0·7	2,500	$\sim$750
HgSe	690	—	$>$10,000	—
InAs	942	0·4	23,000	—
HgTe	670	—	$>$10,000	$\sim$100
InSb	523	0·18	$\sim$70,000	$\sim$600

It can be seen from the Table that few materials would be satisfactory in terms of the specification drawn up, and these present considerable difficulties for their preparation.

(2) The Chalcopyrite Structure.

The next materials to be considered are those with the ternary substituted diamond structure.

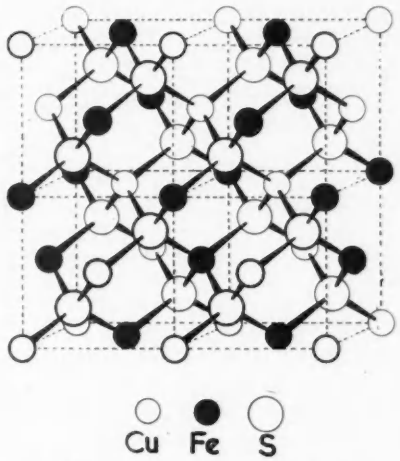


Fig. 3.—The chalcopyrite structure.

Chalcopyrite, copper iron sulphide, is the typical ternary compound. It has the formula $CuFeS_2$ and in the crystal lattice each copper or iron atom is surrounded tetrahedrally by four sulphur atoms, and each sulphur atom by two copper and two iron atoms, as is shown in fig. 3. The structure is, in fact, tetragonal and is slightly distorted from the symmetry of the true diamond lattice,[3] but the deformation is relatively small and all atoms can be considered as forming bonds of the same covalent-ionic type as is found in the sphalerite structure. The valency electrons are shared in common between the atoms, and it seems probable that each copper atom contributes one electron, each iron three, and each sulphur six, making the required total of sixteen electrons for the four atoms of the formula. That iron contributes three electrons is confirmed by the recent discovery of a group of compounds with the chalcopyrite structure in which Group III elements replace the iron atoms.[4] This group can be represented as ABX_2 where A is copper or silver, B is aluminium, gallium, indium or in some cases thallium, and X is sulphur, selenium, or tellurium, giving compounds such as $CuAlTe_2$, $AgInSe_2$ $CuTlS_2$. Rather more than 20 compounds are known which have the chalcopyrite structure.

It is possible to make an approximate prediction of the energy gaps of diamond type compounds by means of the empirical method of electronegativities proposed by Goodman[5]. The application of this method to the chalcopyrite compounds suggests that with these the energy gaps tend to be more concentrated in the range of interest (i.e. 0·8—2·0 eV, as in the specification) than in the sphalerite compounds.

Work has been carried out in these Laboratories on a number of these ternary compounds, and they have been shown to be semiconductors, but it is still too early to furnish much information. The materials seem of much promise for crystal valve applications, thus copper indium selenide ($CuInSe_2$) has a predicted energy gap of 0·9 eV and has shown high back voltage rectification with turnovers in excess of 300 volts. The characteristic of a typical $CuInSe_2$ point contact is shown in fig. 4. compared with that of a production germanium diode. No forming of the $CuInSe_2$ contact had been carried out so that forward resistance is high.

Hall effect measurements on copper indium selenide indicated an electronic mobility of 300 $cm^2\ V^{-1}\ sec^{-1}$ for a polycrystalline specimen ~0·1 ohm cm resistivity. It is believed that the true value for the mobility will be substantially higher.

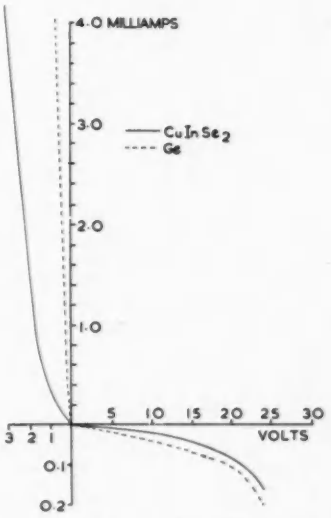


Fig. 4.—Point contact D.C. characteristics.

(3) The Stannite Structure

To extend this study of diamond-type lattices still further some work has been carried out on a quaternary type of diamond lattice. The typical compound, indeed the only material known to crystallise in this structure as far as a search in the literature suggests, is stannite, copper iron tin sulphide, Cu_2FeSnS_4. The structure of

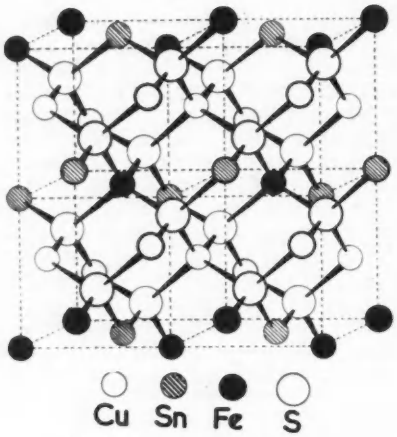


Fig. 5.—The stannite structure.

this compound is indicated in fig. 5. Like chalcopyrite, stannite has a slightly deformed diamond structure[6]. In it each sulphur atom is surrounded tetrahedrally by two copper atoms, one iron atom and one tin atom, while each copper iron or tin atom has four sulphur atoms around it. Stannite is known to act as a point contact rectifier[7], and has a high thermo-electric power. These facts, combined with an electronegativity calculation[5] suggest that it is a semiconductor of relatively large energy gap.

For four electrons to be available for each atom in stannite, in the same way as for sphalerite or chalcopyrite, requires that the iron atoms contribute but two electrons in contrast to the three electrons they contribute in $CuFeS_2$ (see above). Thus iron in stannite can be thought of as behaving differently from iron in chalcopyrite, a difference which could be checked by magnetic measurements. This behaviour is quite reasonable in view of the small difference in energy between iron with two and with three valency electrons. Assuming that it does contribute two valency electrons in stannite it is interesting to speculate that there might exist analogues of stannite in which the iron is replaced by a Group II element in the same way as a Group III element can replace iron in chalcopyrite, as already described. Thus from stannite Cu_2FeSnS_4, one might by substitution obtain $Ag_2CdSnTe_4$, for which electronegativity calculations would predict a useful energy gap. In such cases, however, the expected quaternary compound has not been found to form, as evidently the binary sphalerite compound of the II-VI type is more stable. Thus in the case quoted the product is CdTe and a mixture of silver and tin tellurides.

GENERAL CONSIDERATIONS.

So far attention has been directed solely to physical criteria. While these are outstandingly important in the initial stages of an investigation, a number of practical criteria must eventually be considered in choosing a material suitable for device applications. Thus the melting point should be high enough for a device to be capable of withstanding reasonable temperatures and overloads without destruction, and yet be low enough for standard furnace equipment to be used in its preparation. It is preferable also that the material be stable in air, and not oxidise or hydrolyse easily. It is also necessary that it be obtained in any desired degree of purity or stoichiometry without excessive difficulty. Finally economics must be considered, particularly if it is likely that relatively large quantities of the substance be required. Ideally, the raw materials should be fairly widely available and not excessively costly, while the processing should be capable of being made simple and efficient.

CONCLUSION.

A brief account has been given of some recent developments in the understanding of the electrical properties of a relatively simple crystal structure. This understanding is at present far from complete, and many of the concepts advanced are frankly speculative. However, it is felt that the results obtained from the research programme described suggest that the approach adopted will prove fruitful in dealing with the other and more complicated structures.

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A New Approach to Artificial Lighting

By J. M. WALDRAM, B.Sc., A.M.I.E.E., F.I.E.S.
G.E.C. Research Laboratories.

The new approach to artificial lighting which the author describes is not a new system of lighting, but a departure from the traditional standpoint of considering lighting in isolation. It is shown that the lighting engineer and the architect must collaborate if a building is to achieve its true appearance, and if the various objects in an interior are to be accorded their correct relative values. The results so far achieved suggest many new and interesting possibilities.

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THERE is no architecture in the dark. Lighting is an integral part of architecture : " light and seeing are integral and essential parts of all graphic and plastic art ; in fact, these arts reside in the interplay of the forms created by the sculptor or painter "—or architect— " and the light provided by the lighting artist."* " It is only in light which suits it that an object takes on its true expression. If it is not in its proper light, it is falsified in our eyes and in our feeling. It takes on for us an expression which is not its true expression ; it loses its real significance ; it is deformed for better or for worse. . . . When we light an object, we decide its expression ; we define it or interpret it after our fashion, making it what we should like it to be rather than what it is."†

Certainly lighting can, and often does, quite alter the appearance of an interior, as witness the accompanying pictures of interiors by day and by night, figs. 1 and 2, 4 and 5. It is reasonable to ask whether the distinguished architects who designed these interiors and their artificial lighting are equally satisfied with their day and night appearances.

Windows and daylight are so bound up in architectural design that the forms and lighting have evolved together and are instinctively designed to suit one another, although the daylighting is designed empirically. Moreover, windows are subjected to obvious restraints, which limit the designer to a few well-tried and familiar possibilities, and such limitations are not always a bad thing. We do not always know what to do with unlimited freedom. Artificial light has far fewer restrictions and almost unlimited possibilities ; it leaves us much more free, but there is a very small step between being free and being adrift. Illuminating engineers have classified certain recognisable lighting systems and have shown how to make calculations, and we have sometimes suggested that if only the architect would consult us soon enough in the design of a building, we could tell him how it should be lighted. But our designs are really just as empirical architecturally as those for daylight, but made with less understanding ; our calculations reveal only how much light will result from a given installation on a hypothetical and usually non-existent working plane ; our codes are only rather crude specifications of the illumination necessary for certain tasks. We have talked about co-operation with the architect, and certainly there has not been enough ; but we have been mainly concerned to see that he gives us somewhere to put our equipment and reasonable access to it. We have not really been equipped to co-operate in the architect's proper job, so that our light and his forms could combine to produce a memorable interior.

The fault has not been on the one side only. It could fairly be said that many architects lack the fine feeling for artificial light and its possibilities which they possess for daylight ; they have thought of the lighting equipment merely as architectural embellishment which must look right by day, and have settled its form and position without regard for its function, forgetting

* J. M. WALDRAM, Presidential Address, *Trans. Illum. Eng. Soc.* (London), 1948, Vol. 13, p. 253.

† ANDRE VIGNEAU : ' The Aesthetic Content of Light,' Assoc. Française des Eclairagistes; *Journées de l'Eclairage*, Dijon, 1953, p. 133. (author's translation).

Fig. 1.—An interior by daylight.
(Reproduced by permission of the Secretary, Royal Institute of British Architects.)

that its function is to reveal suitably by night the whole of the rest of their work, which it can either make or mar.

Illuminating engineers throughout the world have not been satisfied with this position, and have for some years been feeling after what has been called " Brightness Engineering " ; but so far there has been little practical result, partly because they have been bogged in a complex mathematical problem, but mainly because nobody really knew what he wanted to do. It is this latter fact which has bedevilled artificial lighting from the beginning. When artificial light was scarce and costly the real problem was hidden behind that of getting the bare necessities for essential tasks, which led to the various Codes ; but that problem has long ago been solved, and the real one remains. We have sought to solve it by extending our Codes and laying down higher illumination values, but this leads nowhere. Specifications for " Brightness Engineering " have been based on notions of comfort or visual performance, some of them on very far-fetched ideas. However, in the last few months there have been developments which may take us in a different direction and which may lead to a real solution and to proper co-operation between the architect and the illuminating engineer.

In September 1953 a sub-committee of the British National Illumination Committee published a Report entitled the " Design of the Visual Field "* which reviewed the position critically and indicated the interrelation of the various researches now in hand ; in January 1954 a paper was read reporting work carried out at the Research Laboratories of The General Electric Company Ltd. which puts the problem in a new light.†

According to the new approach, the problem begins not with the illuminating engineer but with the architect. The proper function of the illuminating engineer is to set limits, based upon the capacity of the eyes, within which a creative designer should work ; the creative design itself is not for him but for an architect or artist. The parallel with a structural engineer is obvious. The first step, therefore, is for the architect to state his conception of what he would wish the building to look like under artificial light. It is stressed that unless the purpose of the interior design is clear, there is little point in trying to achieve it; the result, however carefully contrived, will be aimless and vague. One recalls the stricture passed a few years ago in an architectural journal on a famous modern building : " It combines the technical complexity and vagueness of purpose characteristic of the present age ". We must start with a

* *Trans. Illum. Eng. Soc.*, London, 1953, Vol. XVIII, No. 8, p. 225.

† WALDRAM, J. M. *Trans. Illum. Eng Soc.*, London, 1954, Vol. XIX, No. 4, p. 134.

Fig. 2.—The interior shown in fig. 1, as seen by artificial light.

clear purpose, and in an interior this involves the architecture, the decorations, the furnishings and the lighting all working together in a common design.

The purpose having been formed in the architect's mind, it is necessary to express its essentials in terms which the lighting engineer can appreciate and interpret numerically ; and at this point some new conceptions are necessary. We need new terms and ideas ; they must be simple, they must avoid incomprehensible technical jargon, and—most important—must be conceived to meet the needs and thought of the architect.

The features of the architect's conception which most concern the engineer are three :

(1) The pattern of light and shade in the interior.
(2) The scheme of decoration and furnishing.
(3) The " modelling " or the appearance of solid objects.

There are doubtless others as well, but these three are essential ; they have all been the subject of recent study, and three new methods of expression have been devised.

(*i*) *The Pattern of Light and Shade.* There exists already a fearful array of technical photometric terms whereby " brightness " may be expressed, but for all their complexity they are not suitable for our purpose, because, for good technical reasons, they do not take into account the capacity of the eye to adjust itself to its surroundings: to " get used to the light." Something simpler is wanted which will take this into account, and yet be capable of translation into conventional photometric terms for the benefit of the engineer. Fortunately, a solution is available ; from some work done at the beginning of the war, it has been possible to devise a single and simple scale of a quantity called " Apparent Brightness " which takes adaptation into account, and on which

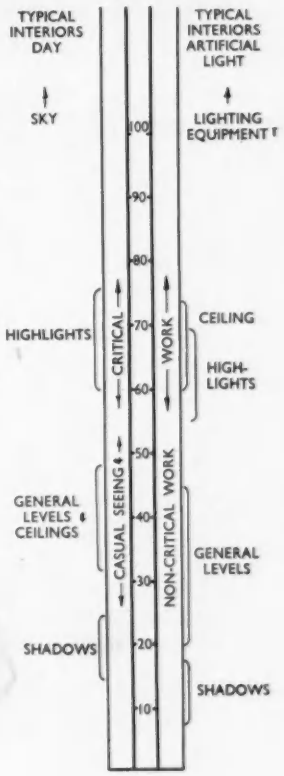

Fig. 3.—Scale of apparent brightness, giving brightness as seen by the eye. Some typical values are marked.

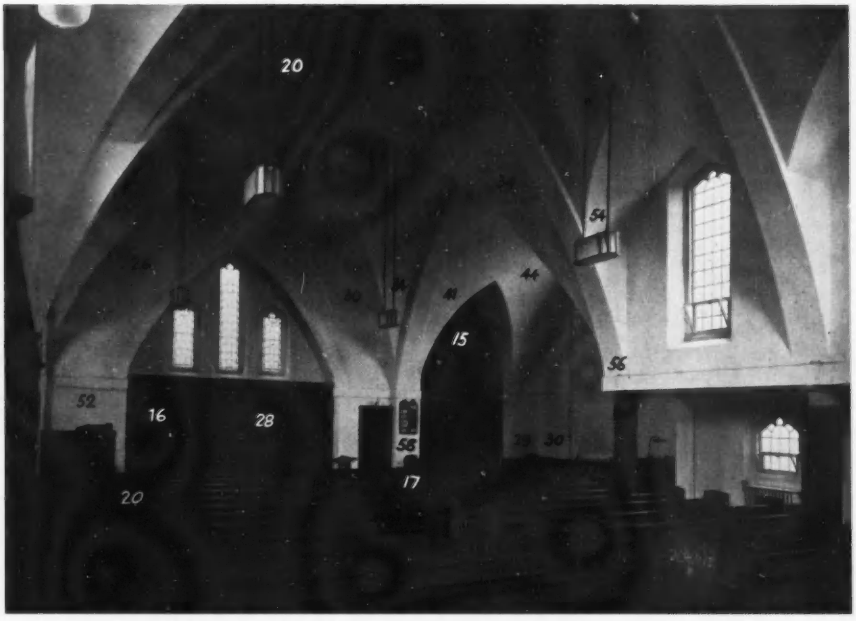

Fig. 4.—Church interior by day. The figures give values of apparent brightness.

we can express light and shade as we see them, at least sufficiently well for the present purpose. An indication of the scale is given in fig. 3, which has marked on it some typical values; other values have also been marked on the accompanying photographs of interiors. Now this scale is new, both to architects and to illuminating engineers, and both have to explore it to discover its meaning. This has always to be done with a new scale, even one of feet and inches. There was, doubtless, the man who first measured his body temperature, found that it was 102 deg. F., but did not know whether it was up or down, whether there was a normal value, or what the difference signified. The use of the scale of Apparent Brightness and some of its meaning will be shown by an example below, and the relation of the scale to the common photometric terms.

(*ii*) *The Scheme of Decoration and Furnishing.* The scheme of decoration will involve the reflection factors—i.e. the tone of the finishes, light or dark—the textures and the colours, for both interior surfaces and for furniture. A complete specification of all three is not necessary and would be too complex to handle. Clearly there are many subtle questions, for example of colour, to be explored in the future, but for the present the important feature is the reflection factor. For this it is sufficient to indicate the finishes on a shade card, as precisely as possible. If such a system as the Munsell System is available, the task of the engineer may be simplified. He needs to know the properties of the finished surfaces. When there are large areas of colour in a high interior, it may be necessary to adjust the colours used for finishing to allow for effects of inter-reflection; it is common knowledge that colours chosen from a flat sample appear much too strong when applied to an interior. For simple cases, it is now possible to work out the necessary dilution of the paint or finish applied to allow for this effect.

(*iii*) *The "Modelling" or the Appearance of Solid Objects.* Modelling has also been intensively studied, and it has been possible to condense a good deal of work into a simple form for architectural specification. What is in effect a "shade card" for modelling has been produced, showing different degrees of modelling from different directions, from which a desired effect can be chosen by the architect; his choice can be interpreted by the engineer in photometric terms, and he can design lighting to produce it. There is not space to discuss this aspect at present in more detail.

Fig. 5.—The church of fig. 4 by night, as originally lighted. The figures give values of apparent brightness.

Fig. 6.—The church of figs. 4 and 5 with modified lighting. The figures show values of apparent brightness achieved. Compare figs. 7 and 8.

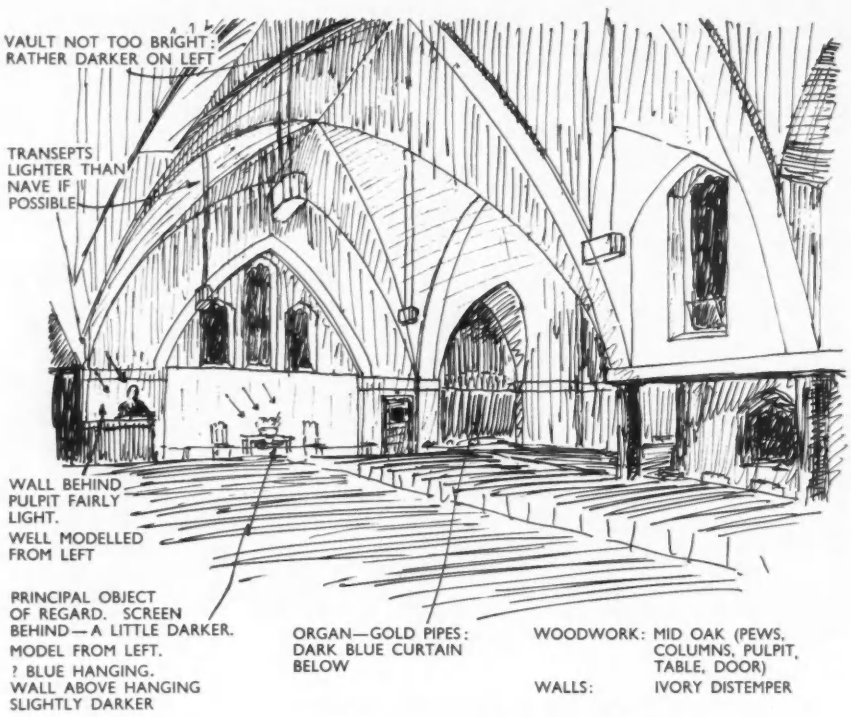
VAULT NOT TOO BRIGHT: RATHER DARKER ON LEFT
TRANSEPTS LIGHTER THAN NAVE IF POSSIBLE
WALL BEHIND PULPIT FAIRLY LIGHT.
WELL MODELLED FROM LEFT
PRINCIPAL OBJECT OF REGARD. SCREEN BEHIND — A LITTLE DARKER.
MODEL FROM LEFT.
? BLUE HANGING.
WALL ABOVE HANGING SLIGHTLY DARKER
ORGAN—GOLD PIPES: DARK BLUE CURTAIN BELOW
WOODWORK: MID OAK (PEWS, COLUMNS, PULPIT, TABLE, DOOR)
WALLS: IVORY DISTEMPER

Fig. 7.—Architect's sketch of interior, indicating the desired pattern of light and shade.

EXAMPLE OF DESIGN BY NEW METHOD.

As an example of a design actually carried through as an experiment by the new method, the Methodist Church shown in figs. 4 and 5 will be studied. It is a simple and rather austere interior, attractive by day, but not very satisfactorily lighted by artificial light; the ceiling is too bright and too featureless, and there is no satisfactory point of repose for the eyes; the Communion Table is dark and the Pulpit dull. In this church an air of mystery is not appropriate; good light is required, but a more satisfactory pattern of light and shade and emphasis is needed.

The first step is to set out a desired appearance by night; this has been done in the sketch in fig. 7, which may be supposed to have been made by an architect. It gives indications of the pattern of light and shade, indicates very roughly the decorations and gives some guidance of modelling. These rough indications must be expressed numerically, using, for the pattern of light and shade, the scale of fig. 3. A series of reference points is taken in the perspective, indicated in fig. 8 by circles, and to each an apparent brightness is assigned, by the architect's judgment, perhaps guided by the engineer. The principal object of regard is the Communion Table, usually decorated with flowers; it is given the value 40, which is towards the upper end of the "general levels" of apparent brightness. The panelling behind it (or the curtain over the panelling) is made slightly less, at 35; the wall above is less again at 32 and the East wall diminishes in brightness up to values of 15-18 at the crown of the vault, a fairly subdued brightness. The transepts are made a little lighter than the nave vaulting in order to distinguish them (at 25); and the right hand (south) side of the nave vault is intended to be a little brighter than the left-hand side, to give it shape and to imply a coherent flow of light in the interior. The wall behind the pulpit is to be about 30, and is to be modelled from the left—if it were modelled from the right, the preacher would be seen down-light by most of the congregation and would look very "flat", like a flashlight photograph, and moreover would

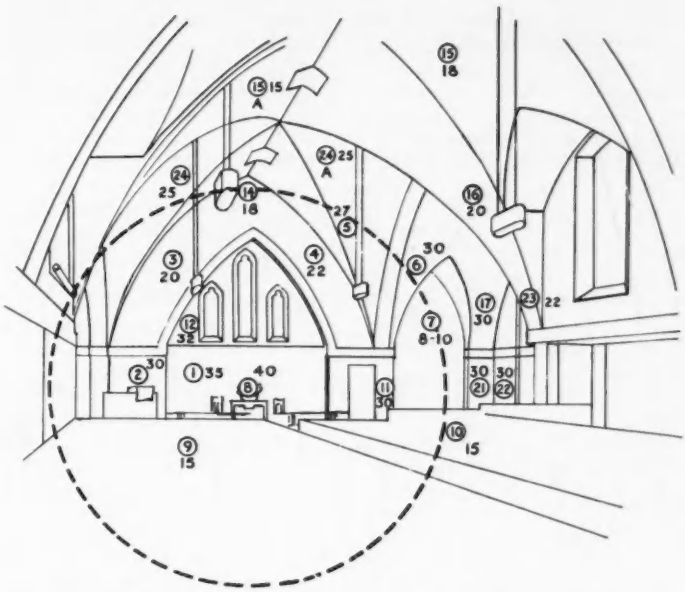

Fig. 8.—The church with the architect's intentions expressed as apparent brightnesses. Numbers in circles are reference points. The dotted circle indicates the region used for estimating adaptation level.

have to look into the modelling light and would experience glare. The Communion Table is also to be modelled from the left; obviously the same direction of modelling must be chosen for both, since they are close together.

The architect has now stated the problem; the engineer takes over.

In order to convert these values into photometric terms, it is necessary to estimate the adaptation level, i.e. the value of apparent brightness to which the eyes will be accustomed. Probably when more is understood about this, it can be determined fairly exactly; but for the present purposes it can be estimated by inspection. A mean value within a circle of about 15° radius, as shown in the sketch, is estimated; probably 25 is not far out in this case. We have now to refer to the set of curves given in fig. 9,

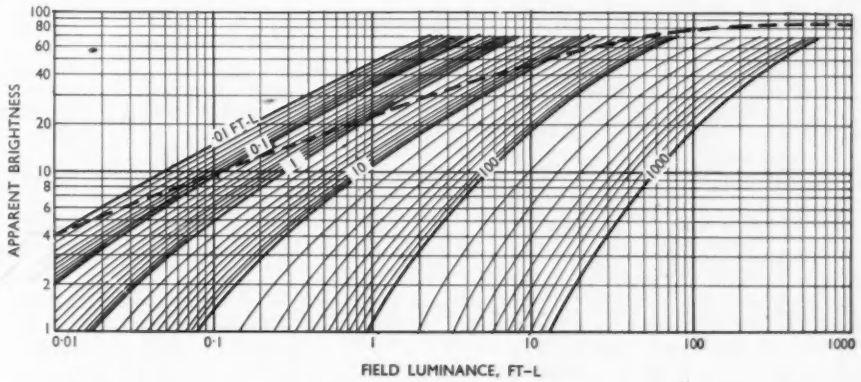

Fig. 9.—Curves relating apparent brightness to luminance (photometric brightness) and adaptation level.

which is the only such set involved. Each curve connects the apparent brightness with the photometric brightness (luminance) in foot lamberts (sometimes formerly called equivalent foot-candles) for a specific value of the adaptation level. To find the appropriate curve, follow the adaptation level of 25, on the vertical scale, along horizontally to intersect the dotted curve ; the point of intersection gives the corresponding photometric brightness of the adaptation level—1·5 ft. lamberts—and the curve to follow is the one running through the point of intersection, in this case one lying between the curves for 1 and for 2 ft. lamberts, which can be interpolated. Using this curve, we can transform all the apparent brightnesses chosen into photometric brightnesses (or ' luminance '), which are read on the bottom (horizontal) scale ; they are marked in fig. 10, and are shown in Table 1, col. 3 for each point.

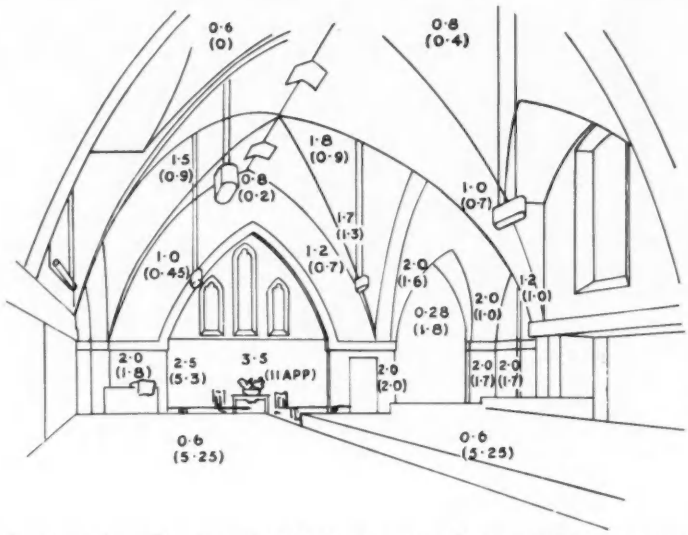

Fig. 10.—Values of luminance in ft. lamberts corresponding to the chosen apparent brightness of fig. 8, and (in brackets) values of direct illumination required to achieve them.

Luminance, or photometric brightness, is the product of illumination and reflection factor ; if we know the reflection factor of each surface involved, the necessary illumination of the surface is found simply. In this case the reflection factors were measured on site, since the building existed ; they appear in col. 4 and, by dividing col. 3 by col. 4, we find the total illumination required on each surface, shown in col. 5.

Now the total illumination required has two components : the light received directly from the lighting equipment, and the light received from all the other bright surfaces in the interior. The latter factor has hitherto greatly complicated the problem, because it has been treated as a problem of inter-reflection ; but a much simpler solution presents itself if we start by specifying what we want. Each surface concerned is surrounded by a " sky ", which is composed of all the other surfaces ; and the brightness of all these surfaces is already known, because we have specified them, and they are already marked on fig. 10. To find the illumination which will result from them is then a fairly simple problem in daylight illumination, and in fact for many purposes it can be solved by inspection ; in more complex cases, the Building Research Station protractors can be used. It will be recalled that if a surface is faced by a complete sky of brightness B ft. lamberts, it will receive an illumination B lum. sq. ft. (foot-candles). One half of this illumination comes from the part of the " sky " extending from the horizon to 45° and the remainder from 45° to the zenith. This notion, suitably oriented, can be applied to any point in the interior, and the illumination from a non-uniform " sky " can be calculated or estimated. Take for example point 15, near the crown of the vault. It faces an inverted " sky " of which the part from

45° up to the " zenith " will be mostly the pews, of luminance 0·6 ft. lamberts ; they will account for about half the illumination at point 15. The other half will mainly come from the walls and vault opposite, which will be from 0·6 to about 1·0 ft. lamberts. The illumination received by inter-reflection at point 15 will evidently be about 0·7 lum./sq. ft.

This process is repeated for each point, and appears in col. 6. Clearly, if we subtract col. 6 from col. 5, the remainder is the direct illumination which must be provided from the lighting equipment ; this is shown in col. 7, and is marked in fig. 10, in brackets, for each point. The design of a lighting system to provide these illuminations is a matter of fairly straightforward illuminating engineering.

One or two points are of interest : for example, if the reflection factor of the wood panelling is taken for point 1, a very high illumination of 24 lum./sq. ft. must be provided on it, but the off-white wall just above it needs only 2 lum./sq. ft. This is impracticable ; to avoid the difficulty a curtain of some lighter material could be provided over the panelling ; the architect will have to suggest an appropriate colour. If its reflection factor is raised to about 0·4, which will permit a fairly strong colour, the illumination required will drop to 5·4 lum./sq. ft., which is reasonable. At point 15a, however, on the north vault, the indirect light is sufficient and no direct light is needed. Had we specified a lower brightness at this point, it would have been impossible to achieve it with this reflection factor. The total illumination on the pews, 6 lum./sq. ft. is adequate for a church ; had it not been, an adjustment would have been necessary.

By a series of simple calculations which need not be described, based on the luminances in the existing installation, it was concluded that the direct illuminations on the vault were much too great with the existing installation, and there was too much light on the left (north) side. The fittings were, therefore, temporarily modified by putting an opaque white top on them, which slightly increased the downward illumination but put less light to the vault; the north side of each fitting was further obscured by sticking detail paper over it. A curtain of the proper reflection factor was hung over the panelling, and two 150-watt reflector lamps attached to the left-hand (north) lighting fitting next the Communion Table, directed at the

TABLE 1

1 Point	2 Apparent Brightness (Design)	3 Luminance Required (ft. lamberts)	4 Reflection Factor (Measured or Designed)	5 Total Illum. Required Lum-ft.^{2}	6 Inter-Reflection Component	7 Direct Illum. Required Lum.-ft.^{2}
1	35	2.5	.10	25	0.9	24 impracticable: vary refln. factor
		change to	·4	6·25	0·9	5·35
2	30	2·0	·75	2·7	0·9	1·8
3	20	1·0	·75	1·35	0·9	0·45
4	22	1·2	·75	1·6	0·9	0·7
5	27	1·7	·75	2·3	1·0	1·3
6	30	2·0	·75	2·7	1·1	1·6
7	8-10	0·28	·10	2·8	1·0	1·8
8	40	3·5	·3 (flowers)	12	1·0	11 approx.
9	15	0·6	·10	6·0	0·75	5·25
10	15	0·6	·10	6·0	0·75	5·25
11	30	2·0	·75	2·7	0·7	2·0
12	32	2·2	·75	3·0	1·0	2·0
14	18	0·8	·75	1·1	0·9	0·2
15	18	0·8	·75	1·1	0·7	0·4
15a	15	0·6	·75	0·8	0·8	0
16	20	1·0	·75	1·3	0·6	0·7
17	30	2·0	·75	2·7	1·7	1·0
21	30	2·0	·75	2·7	1·0	1·7
22	30	2·0	·75	2·7	1·0	1·7
23	22	1·2	·75	1·6	0·6	1·0
24 (24a)	25	1·5	·75	2·0	1·1	0·9
adapting level (estimated)	25	1·5				

Table and screened from the pulpit; these, it was calculated, would give the required illumination on the Table and curtain. For the modelling of the pulpit and preacher, a single reflector lamp was mounted high up in the north transept ; its position and power were found by calculation for the direction and amount of modelling required. There were two reflector lamps used in the south transept for lighting the choir, which were also turned on, to increase the brightness of the south transept.

These arrangements were quite crude, and most of them could not be based upon measurement because the performance of the main fittings was not exactly known either before or after modification. Nevertheless, the result, which is shown in fig. 6, was closely what was intended, and measurement showed that the desired modelling and apparent brightness pattern had been achieved quite closely. It should be stressed that the interest is not in the particular result achieved, nor in the quite simple means used to achieve it, so much as in the fact that the desired effect was specified, and was achieved by *predicted* methods, first time and without experiment.

The saving of time and effort and uncertainty which this procedure may bring about in the lighting of new and important interiors, in which experiment may be impossible when the building is unfinished, and alteration impossible when it has been, will be evident to all who have experienced the method of cut-and-try which has usually been necessary. The ideas here set forth are new and experience has yet to be gained with them; but they promise much for the future. In this article nothing has been recorded of the new tools which the lighting engineers are shaping to help them ; already they have worked out some great simplifications in their calculations ; they can predict the installations to give desired brightness patterns and modelling. The problems of colour are technically of baffling complexity, but progress has been made with them.

The new approach is not a new system of lighting. It may lead to arrangements which an experienced man might well have come to empirically. But it may well lead to new trends. For example, it is clear that there is no necessary virtue in arrays of lighting fittings hung throughout the interior space, unless the architect needs them for decorative effect. Such systems may, however, be used for the basic lighting, with " trimming " by such devices as reflector lamps concealed in the positions necessary for modelling, either at the walls or concealed in large lighting fittings. It is conceivable that we may have lighting fittings the distribution of light from which can be modified without spoiling their form. We may find that our present lighting schemes are making the ceilings much too bright, and may return to a balance of brightness nearer to what occurs in daylight. But it is not to be supposed that we must copy the daylight effect. By day the view through the windows is a natural object of regard, and the room seems a pleasant shelter from which we may look at it ; but by night the windows are dark and blank, and another focus and emphasis are needed ; otherwise the room may seem aimless. We have new possibilities available with fewer restrictions : we must work out the best ways of using them in their own right, without copying the limitations of daylight, so that they combine with the architectural forms and decoration in a common purpose to form a memorable result.

An Automatic System of Control of Boiler House Auxiliaries

WITH SPECIAL REFERENCE TO THE USE OF GRID-CONTROLLED MERCURY ARC RECTIFIERS.

By J. BRIDGES, A.M.I.E.E., Chief Engineer, Electroflo Meters Co., Ltd.
and E. C. DAVIES, A.M.I.E.E., Witton Engineering Works.

In modern power stations, maximum efficiency of the steam raising plant is of the utmost importance to the economic running of the station, and this is best assured by arranging for automatic control of the boiler plant.

This article outlines the conditions which must be satisfied in service, and describes a fully automatic scheme which has been developed jointly by the Electroflo Meters Co. Ltd., and The General Electric Co. Ltd., and installed in the Huncoat Power Station of the British Electricity Authority.

INTRODUCTION.

FOR maximum efficiency combined with maximum economy in the operation of steam raising plant two essential conditions must be satisfied. First, the heat input to the boiler must balance the heat output (load) at all times, and, second, the correct relationship between air and fuel must be consistently maintained.

In everyday operation these conditions have to be met when contending with (*a*) varying load (*b*) low rating periods (*c*) changes in the calorific value and moisture content of the fuel and (*d*) progressive deterioration in the condition of the plant. If the boiler is under manual control, the operator must make, or observe, a measurement each time a correction is required, and exercise his judgment to determine its direction and magnitude before he can take the appropriate action. The correction can seldom, if ever, be exactly that required, while the inherent time lag is an added disadvantage even if the attendant is more than ordinarily vigilant and skilful. Clearly the only solution to the problem is the use of automatic control whereby adjustments are effected promptly and accurately immediately any change in the operating conditions occurs.

The part which electric drive can play in this direction has been closely studied by The General Electric Co. Ltd., in full collaboration with some of the leading manufacturers of automatic boiler control equipment. Control schemes have been developed suitable for the electric drives installed in modern boiler plants using pulverised fuel or oil firing, a notable example being that at the Huncoat Power Station, Accrington, of the British Electricity Authority.

In this installation the auxiliaries are driven by variable speed D.C. motors operating in conjunction with both grid-controlled and constant voltage mercury arc rectifiers. The automatic control scheme was developed jointly by Electroflo Meters Co. Ltd., and the G.E.C. and is covered by Patent Specification No. 662971.

The boiler plant was supplied and installed by Simon-Carves Ltd., who were the main contractors, with Kennedy and Donkin acting as consultants. Three pulverised fuel fired boilers are installed with two more boilers for future extensions, each having a maximum continuous evaporation of 305,000 lb. per hour, steam pressure 625 lb. per sq. in., final steam temperature 860 deg. F.

Before a description of the control system is given, the operation of the grid-controlled rectifier is briefly explained, because it is an important electrical feature in the scheme.

THE GRID-CONTROLLED RECTIFIER.

The grid-controlled mercury arc rectifier provides one of the most rapid and accurate means of controlling power up to any required value. The rectifier is fed through transformers

directly from the power station auxiliary A.C. supply. Its D.C. output depends upon the phase of the grid voltage pulses which are controlled by a phase-shifting apparatus.

When used in an automatic boiler control scheme, the phase-shifter is actuated by the appropriate device in the automatic control system and this operates immediately there is any alteration in boiler pressure and/or steam flow. As the rectifier output varies instantaneously with any change in the phase of its grid voltage, there is a minimum of delay between the operation of the phase-shifter and the response of the motor connected to the rectifier.

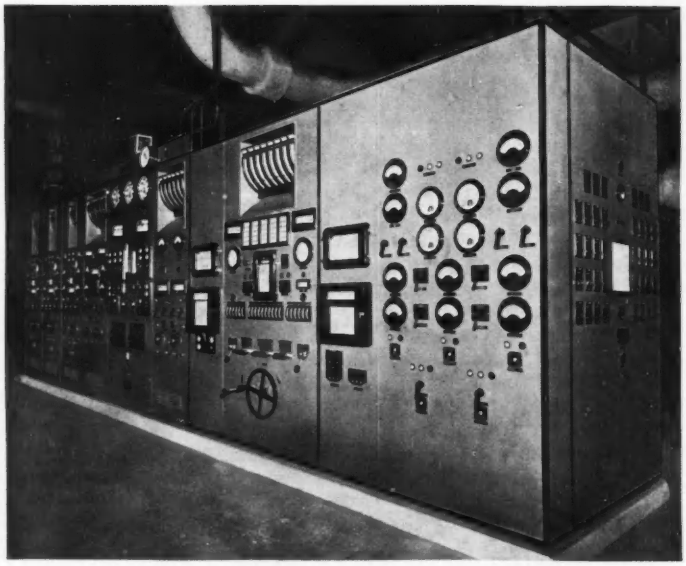

Fig. 1.—One of the boiler house control boards.

It will be appreciated from the foregoing that the grid-controlled rectifier constitutes a powerful and effective link between the automatic control apparatus and the motors driving the boiler auxiliaries.

THE ELECTROFLO-G.E.C. SYSTEM.

As already mentioned, this system employs variable speed D.C. motors for all the auxiliary drives, the motors obtaining their power from mercury arc rectifiers. Control is fully automatic, steam pressure and maximum combustion efficiency being preserved irrespective of changes in load, characteristics of the fuel or progressive deterioration in the condition of the plant.

Briefly, these requirements are met in the following way :

(1) Steam pressure is used as the index of balance between steam demand (load) and steam supply (boiler evaporation).

(2) A change in load (steam pressure) varies the quantity of fuel fed to the boiler by an amount necessary to restore boiler pressure.

(3) A change in load (steam pressure) also varies the quantity of air for combustion supplied by the forced draught fans.

(4) The fuel/air ratio is maintained by continuous measurement of steam flow and air flow, any departure from the desired ratio being corrected by an automatic alteration to the quantity of fuel fed to the furnace, thus correcting for changes in quality and condition of fuel.

(5) The combustion chamber pressure is maintained at the desired value by control of the induced draught fan.

OPERATION.

A diagrammatic arrangement of the scheme is shown in fig 2 from which it can be seen that the electrical equipment is operated by power cylinders, each under the control of the regulators which are responsive to changes in load and to the variable being controlled.

MASTER CONTROLLER.

The master steam pressure controller continuously measures steam pressure in the main steam header and sends out air under pressure to the control system. This air pressure is called the master loading pressure since its magnitude is dependent upon the load and is used to co-ordinate the fuel and air flow regulators.

The master loading pressure is distributed to the boiler control panels (figs. 1 and 3) where maximum and minimum loading units preset the range of control which will be accepted by each boiler. The master loading pressure is indicated by the height of one column on a three-tube loading manometer, air and fuel

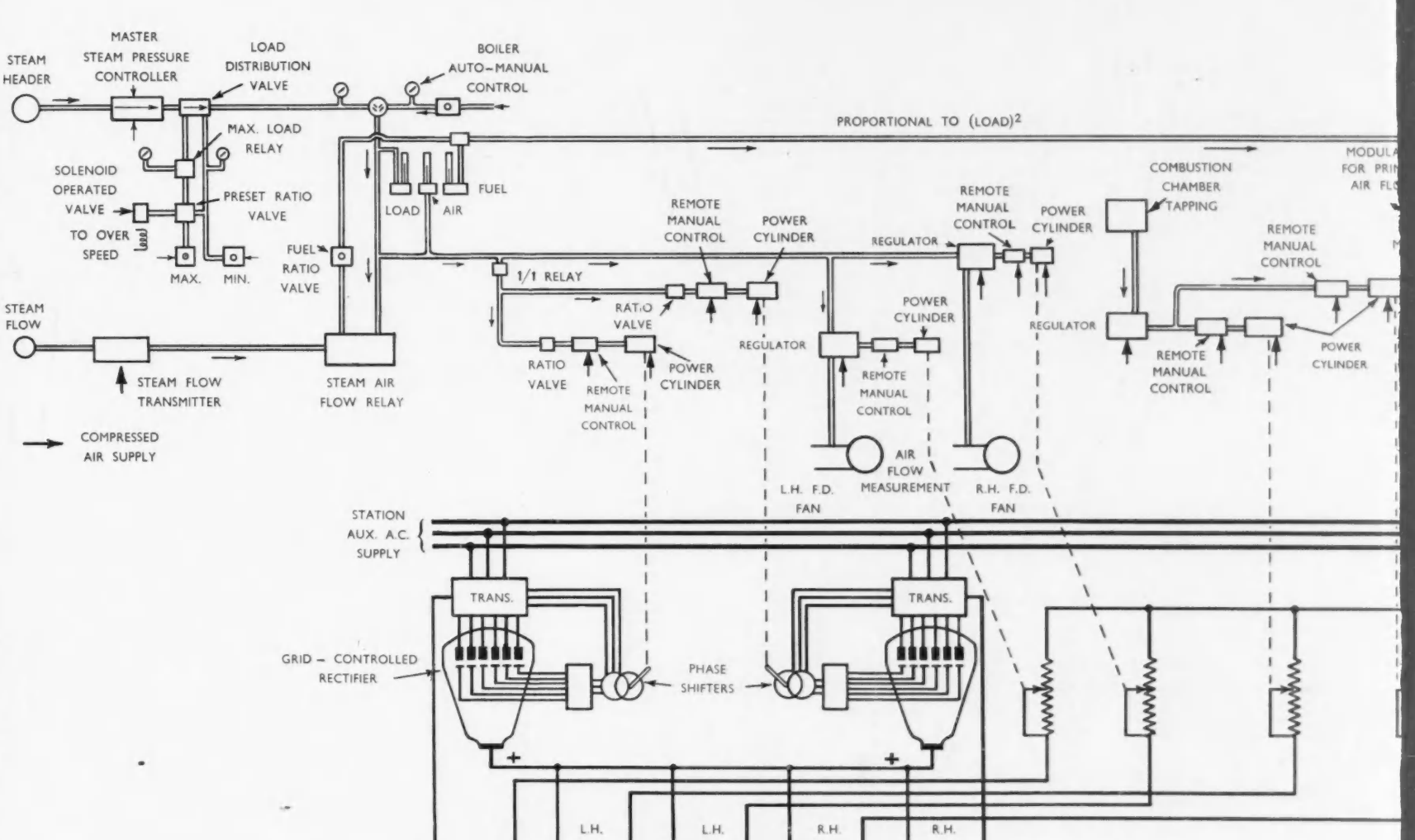

Fig. 2.—Diagrammatic arrangement of the automatic boiler control equipment.

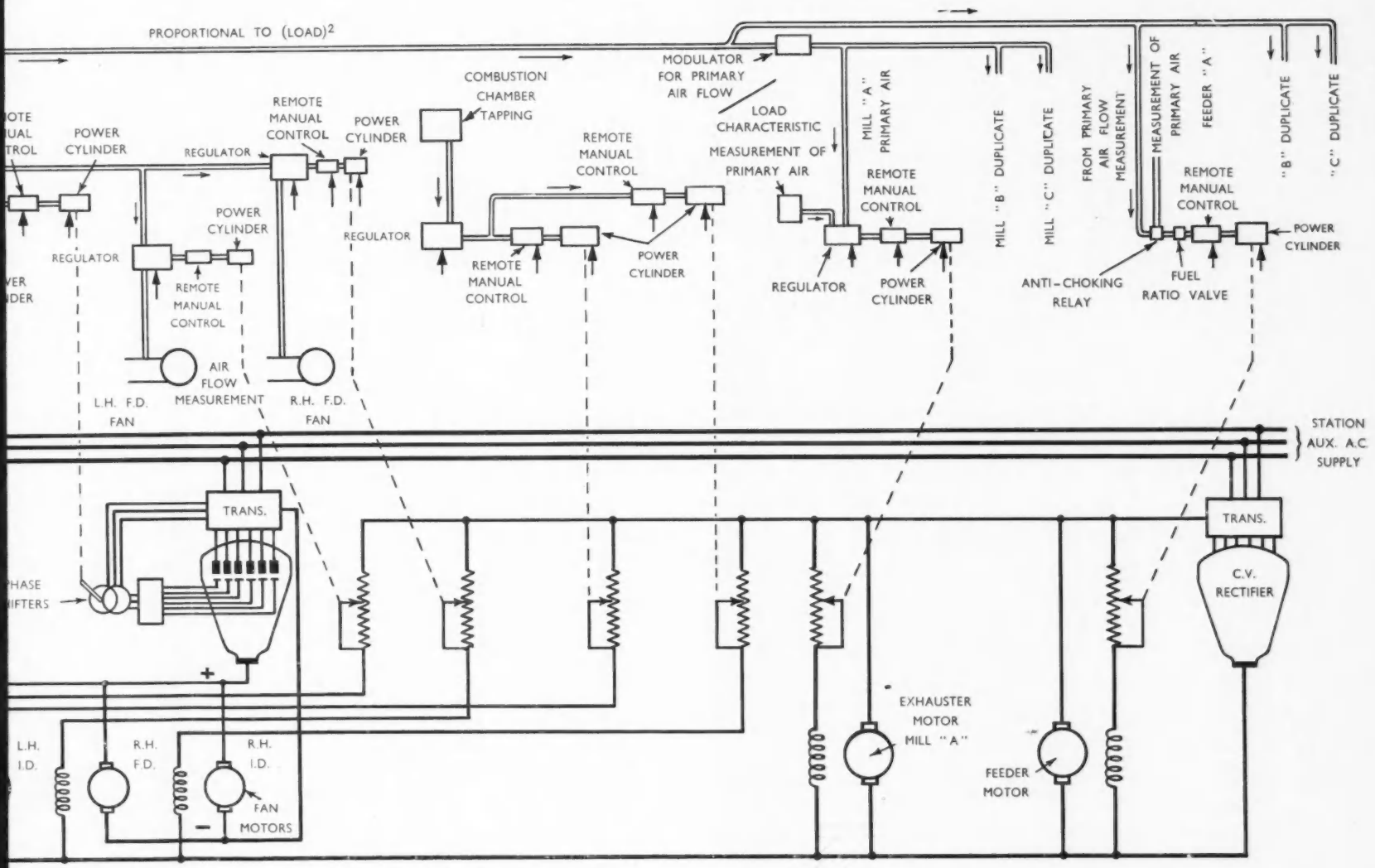

Fig. 2.—Diagrammatic arrangement of the automatic boiler control equipment.

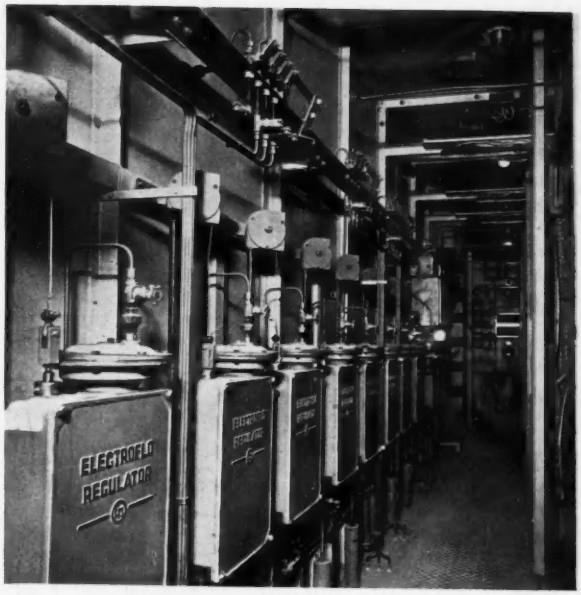

Fig. 3.—Interior of one control board showing regulators operating rheostats and phase shifters.

loading being shown on the other two columns respectively. This is an important feature of the system in that it presents to the operator a readily understood indication of the working of the controls. Provision is made for changeover to a manually set master loading pressure. Thus, if so desired, a boiler may be operated at constant evaporation rather than constant pressure.

From the boiler control panel one branch of the master loading pressure is connected to the fuel controls while a second branch is connected to the air flow controls.

FUEL CONTROL.

To consider first the control of fuel, the motors driving the fuel feeders (fig. 4) and the pulverised fuel mill exhausters (fig. 5) are supplied from a constant voltage rectifier, speed variation being effected by means of field rheostats. By reference to fig. 2, it will be seen that the master loading pressure acts on the regulators controlling the positions of the power cylinder. Thus a change in load causes the power cylinders to move and adjust the field rheostats of the feeder and exhauster motors to balance the new load condition.

The master loading pressure is compared with boiler steam flow at the steam flow/air flow relay and the loading pressure sent out to the feeder and exhauster regulators is given a positive or negative correction when there is a departure from the desired steam flow/air flow ratio.

A modulator in the master loading pressure line to the exhauster regulator ensures that the correct relationship exists between load and the primary air flow as measured by the exhauster regulator.

Anti-choking relays safeguard the mills against overfeeding. Should the mill tend to choke, the exhauster regulator increases the speed of the exhauster to maintain the primary air flow. If this fails to clear the mill, further choking will reduce the primary air flow below the normal minimum value so causing the anti-choke relay to operate and re-

Fig. 4.—0·5/1·5 h.p. motors driving feeders to the pulverising mills.

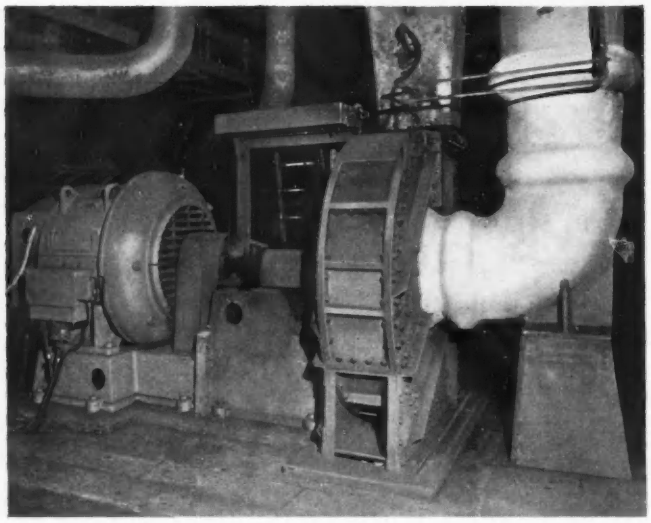

Fig. 5.—135 h.p. motor driving exhauster fan.

duce the master loading pressure of the feeder regulator until the speed of the feeder motor is brought down to its minimum value.

AIR FLOW CONTROL.

It will be seen from the diagram (fig. 2) that the master loading pressure also acts on the regulators controlling the forced draught fans (fig. 6). Since the master loading pressure is related to load, the fan speed will be adjusted to produce an air flow proportional to load. Hence both fuel and air quantities are co-ordinated by the control system to establish maximum combustion efficiency and the correct heat input demanded by the load.

The armatures of the motors driving the boiler fans are supplied from two grid-controlled rectifiers, each rectifier being connected to one induced draught and one forced draught fan motor so that these two fans operate as a pair. The fields of the machines are excited from the constant voltage rectifier.

The main speed control of the motors is obtained by varying the armature voltage and is initiated by the master loaded, positioning type regulators operating the phase-shifters, which in turn alter the output voltage of the grid controlled rectifiers and consequently the armature voltage of the motors. Thus an immediate response is obtained in the speeds of the fan motors. In order that a precise adjustment is made, a continuous measurement of air flow is taken by the forced draught regulators and balanced against the master loading pressure, any error in air flow being corrected by an automatic adjustment to trimming rheostats in the motor field circuits.

The system is so arranged that the phase-shifter regulators are the first to operate, the field rheostat control being tuned to provide stable operation.

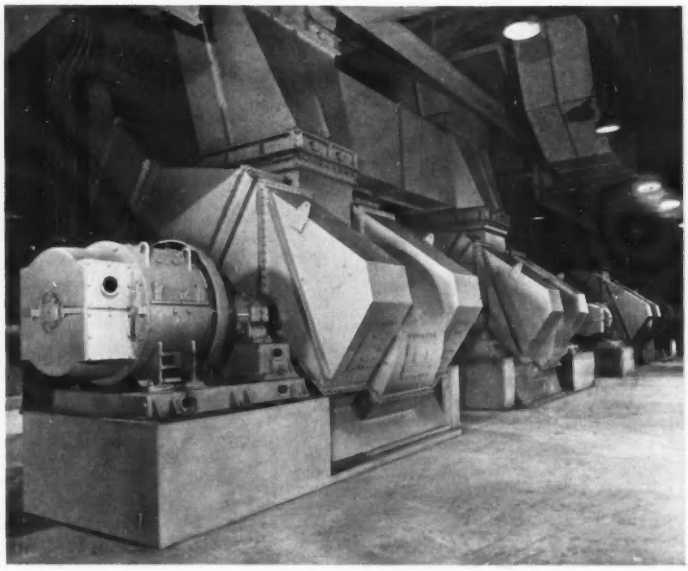

Fig. 6.—55/112 h.p. motors driving the forced draught fans.

COMBUSTION CHAMBER CONTROL.

Because each grid controlled rectifier serves one forced draught and one induced draught fan motor, a change in boiler load will change the voltage applied to the armatures of the induced draught fan motors (fig. 7). Accurate control of combustion chamber draught is provided by a separate regulator operating the shunt field rheostats of the induced draught fan motors. This regulator is of the measuring type, balancing combustion chamber draught against a preset value.

MANUAL OR SEMI-AUTOMATIC OPERATION.

Convenient arrangements are made for manual operation when so desired. It is important that it should be understood, however, that this method of control means the determination of air pressures by the manual control of handwheels which govern the operation of the control units and their associated power cylinders. Thus operation of the boiler manual control, which is better described as "semi-automatic" control, affords a constant rating control, i.e. the individual regulators still operate automatically, but do so in order to maintain a constant rating as set by the control handwheel. During manual control, therefore, the speeds of all units are still maintained at their correct relative values and mal-adjustment of individual controls is avoided. On the other hand, in fully automatic control the pressure in the air lines, which is determined by the master steam pressure controller and steam flow/air flow measurement, automatically reflects the load on the boiler at any instant.

CONCLUSION.

It will be appreciated from the description given that the operation of the Electroflo-G.E.C. system does not rely on predetermined characteristics of each unit in an attempt to follow the varying demands of changing boiler load conditions which, with the vagaries of the quality of fuel and other variable factors, become extremely difficult to predict. Instead, the principle employed is to measure continuously the requirements for each individual unit and to control the speed, and hence the operation, of each, independently and accurately.

As a result of the close collaboration of all concerned, fully automatic working of the boiler plant at the Huncoat Power station was introduced smoothly, and the subsequent performance of the equipment has given complete satisfaction and fully justified the claims made for this system of control.

ACKNOWLEDGMENTS.

The authors wish to acknowledge the help given by the British Electricity Authority in granting permission to photograph and describe this installation and to use the illustrations and data in the foregoing article.

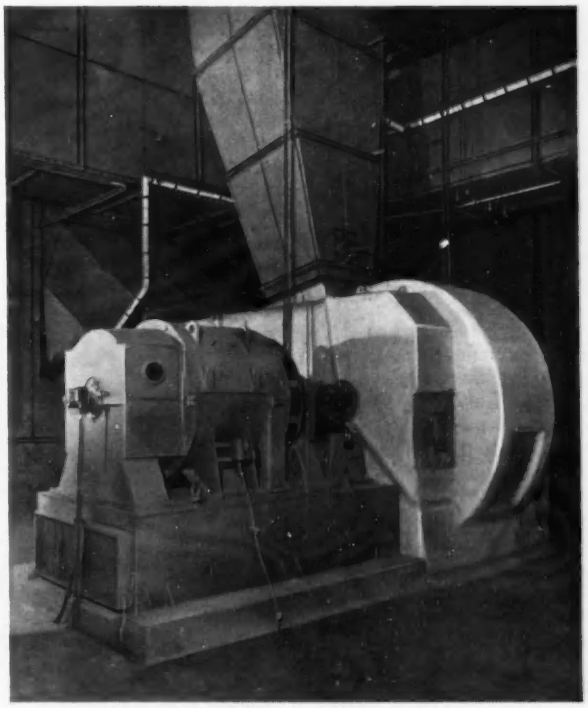

Fig. 7.—115/205 h.p. D.C. motor driving one of the induced draught fans. The motor is arranged for bedplate cooling.

Signal Equipment for the Toronto Subway

By J. SULSTON, M.I.R.S.E.

The Siemens and General Electric Railway Signal Company, Ltd.

INTRODUCTION.

THE rapid transit subway beneath Yonge Street, Toronto, is the first underground urban railway in Canada. It was brought into being by the Toronto Transit Commission to meet the increasing demand for better travel facilities, particularly during peak hours. The signalling system was installed by The Siemens and General Electric Railway Signal Company, Ltd., who were responsible for the design and manufacture of the equipment, and to whom the contract was awarded in March, 1951. The subway is designed for an ultimate capacity of 40,000 passengers an hour in each direction, and signalling of the most modern character was specified by the Commission.

The subway is some 4½ miles in length, partly in two tunnels and partly open cut, and generally follows the route of Yonge Street. The southern terminal is Union Station, situated adjacent to the main line Union Station operated jointly by the Canadian National and Canadian Pacific Railways. From Union the line runs east for a short distance and then, turning north parallel with Yonge Street, passes through ten intermediate stations to the northern terminal at Eglinton (fig. 2).

Union has an island platform with a scissors crossover and the necessary incoming and outgoing signals controlled from a small interlocking plant; outside these limits the signalling is operated automatically by the passage of trains until the interlocking area at Davisville is reached.

Davisville is the largest station on the subway, with three platforms and an interlocking plant which controls all points leading to the storage tracks and also those to the carriage sheds. In addition, Eglinton terminal is controlled from the Davisville interlocking control panel.

All the tracks are equipped with track circuits and throughout the automatic section three-aspect colour light signals are used. These display 'Red'—Stop; 'Yellow'—Proceed with caution, prepared to stop at the next signal ahead; and 'Green'—Proceed. Automatic train stops are associated with each running signal. Placed at strategic positions through the automatic sections are scissors cross-

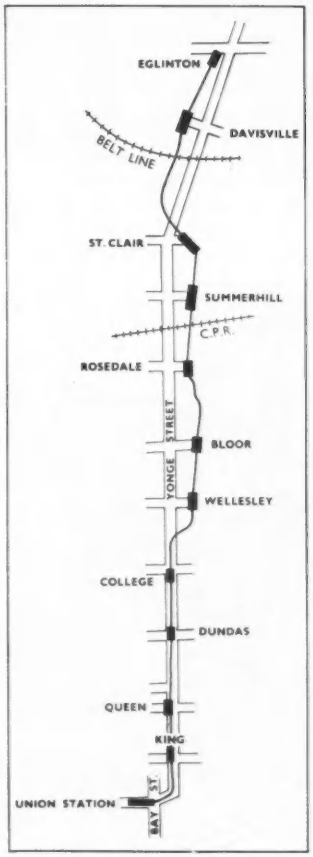

Fig. 1.—Route of the Toronto Subway.

Fig. 2.—Eglinton Station showing point machine and signal.

overs, electrically released but manually operated. These are for use in emergency when it may be necessary to turn trains back, or should occasion demand, the southbound or northbound tracks can be isolated to make single line operation possible to the next crossover while still under complete control.

At the terminal stations the controlling circuits are so arranged that the signalling system may be switched to the automatic operation of points and signals, the setting for each train movement being responsive to the occupancy and clearance of certain track circuits; in addition to this, an automatic train despatcher may be used.

RELAY INTERLOCKING.

The relay interlocking system employed has been the subject of continuous development since an original pioneer installation at Thirsk, England, in 1935, and it fully met the specification requirements of the Toronto Transit Commission.

Relay interlocking was introduced, as it was considered it would provide a more convenient method for the signalman to operate the signals and points under his control, by placing before him a complete picture of the area controlled. This picture is in the form of a track layout diagram upon which the signal, point and track circuit indications are mounted in their relative positions as on the track (fig. 3).

With the S.G.E. system of relay interlocking, a route setting key is fixed on the track diagram in a position corresponding to the signal on the ground which governs entry to the route controlled by the key. Where a signal controls the entry to a number of routes, the route desired may be

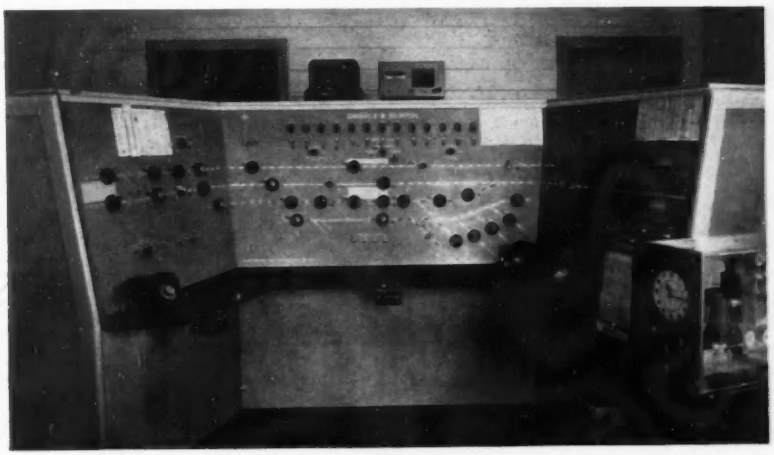

Fig. 3.—Davisville and Eglinton control panel.

selected by the use of a special rotary type selector key, alternatively the system can provide a key for each route. The Toronto subway installation employs the former method.

Interlocking relays with normal and reverse contacts, which correspond to the normal and reverse contacts of a lever frame, are used for each signal and pair of points. Operation of the keys initiates changes in the relay positions, the relays being electrically interlocked, one with the other, as are the levers in electric lever interlocking. The use of relays enables the route setting system to replace, without complication, the older system of individual operation for points and signals.

To set up a route requires only a turn of the appropriate route key. From this point onwards the whole operation follows in automatic sequence, which may be observed by the changes shown by the indications on the track diagram.

The interlocking relay has four windings, controlled as follows :

From Normal to Reverse.

1. Reverse interlocking (equivalent to a lever lock effective in the normal position).
2. Reverse track coil, controlled by the track circuits and detection (equivalent to a lever lock effective in the reverse indication position).

From Reverse to Normal.

3. Normal interlocking coil, controlled by the reverse interlocking (equivalent to a lever lock effective in the reverse position).
4. Normal track coil, controlled by track circuits (equivalent to a lever lock effective in the normal indication position).

Signal lock relays are magnetically latched in their normal position. Upon energisation of the reverse interlocking coil (RLQ) this latch is released and forces the normal front contacts to break (fig. 4).

Point lock relays are latched in their normal and reverse positions.

RELAY INTERLOCKING CONTROL PANELS.

Two relay interlocking control panels are installed, one at Union terminal station for controlling the scissors crossover and storage sidings, and the other at Davisville for controlling Davisville interlocking area and yard together with the remote control of the scissors crossover at Eglinton terminal station.

The control panel at Union (fig. 5), four feet in length, consists of a metal framed cabinet panelled with Warerite, a modern plastic bonded laminated board, with a removable rear panel affording access to all fittings and terminals.

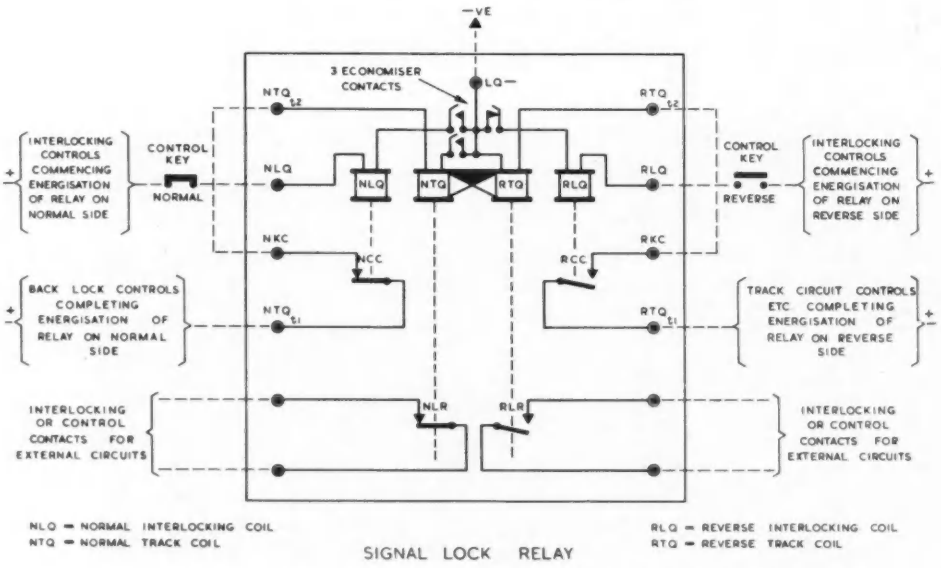

Fig. 4.—Diagram showing the operational sequences of the interlocking relay.

The track diagram is inclined at 45° and consists of a Warerite panel, matt green finished, on which the track layout is depicted by various coloured lines, the extent of each colour representing a complete track circuit. The track colouring together with the signal symbols and lettered information is processed into the surface of the Warerite to present a smooth and durable non-staining surface.

The control panel at Davisville is of similar construction and finish but of larger dimensions. To make it convenient for one operator to control it, the panel is arranged with a 5 ft. centre section with 3 ft. wing sections adjoining it at either side ; the upper front half of each section supports the track diagram inclined back 10° from the vertical.

" Perspex " light guides provide the track circuit and signal indications. The operation of a route key illuminates the route controlled by that key with a series of spaced white lights. Points in the route display a flashing red light while in transit, which changes to a steady white light along the line of the route when they have completed their movement, and their detection relay has operated. The signal indication adjacent to the operated route key then changes from red to either green or yellow, depending upon whether a main or subsidiary signal has been selected ; a flashing yellow light indicates that a subsidiary signal has been cleared to yellow but the motorman has yet to operate the ' key-by ' (see page 242) facility for lowering the train-stop at the signal.

A train entering the route will cause the signal indication to restore to red, and the white route lights change progressively to red as the track circuits become occupied ; the red lights themselves becoming extinguished when the track circuits clear due to the passage of the train.

Once a route has been established and the signal governing the route displays " proceed " for an approaching train, the route is held locked by the occupation of track circuits in the approach to the signal (approach lock) and those beyond to the end of the route.

Signal approach locks can be released by restoring the control key to normal and waiting for a time element relay to complete a release circuit over its operated contacts. Time settings are 30 seconds for a main signal and 15 seconds for a subsidiary signal.

Manual emergency release keys are provided along the top half of the control panel for the individual control of all power points. These keys are of the three-position type, turned to the centre position when route setting control is in force. Associated with each key is a push button, normally sealed; the operation of this button introduces a 30 seconds' time delay before the points can be operated in the event of failure of the point locking track circuit. Other control keys are used to set up the following :

1. ' Reverse traffic working ' : used when single line working may be called for in the event of an emergency or for running trains during the night without interruption to track maintenance schedules.
2. ' Fleeting ' : a facility provided only at Davisville to permit the operator to switch the main line controlled running signals of either or both of the northbound and southbound lines to automatic operation.
3. ' Manual working/automatic working ' : these keys on the two panels are used to select the method of working the reversing crossovers at Union and Eglinton terminal stations. When in 'manual', Union crossover

Fig. 5.—Control panel at Union Station.

is controlled from Union panel and Eglinton crossover from Davisville panel. In 'automatic', control is vested in the sequential occupancy and clearance of the platform track circuits, while remaining subject to the full protection of interlocking, approach locking and back locking. The circuiting also permits, while in 'automatic', moves to and from the storage sidings at Union Station.

The clearing of the platform starting signals at Union and Eglinton under 'automatic working' is normally controlled by an 'automatic train despatcher'. This was provided by the Toronto Transit Commission and is a trolley mounted device arranged for plug-in connection to the control panel. When this is used the signalling route setting relays are controlled through the medium of a synchronously driven tape spool, code marked in accordance with the time-table arrangements. Any unforeseen occurrence which calls for a variation in these scheduled times is covered by providing platform push button control of the starting signals, which permit control by a local traffic official without the necessity of having to revert to 'manual working' on the control panel.

Supplementing these arrangements in 'automatic working' are the 'platform out of service' push buttons which, when operated, take a selected platform out of service without interruption to the automatic functioning of the train reversing movements.

Also displayed on the control panel are lamps for 'power off,' 'ground detection' and other miscellaneous indications backed up by audible alarms which can be silenced by 'acknowledge' pushes.

RELAY ROOMS.

The relay room at Davisville (fig. 7), located directly beneath the control room, houses all relays and associated equipment operated from the control panel, relays for signal and point control and indication, track repeat relays and so forth.

The plug-in relays, of which there are 420, are mounted on special resiliently fixed steel racking, arranged in two runs the length of the relay room.

Wires to the relay racks from the panel and the fuse and terminal boards are run in overhead wire chases; inter-rack and rack wiring is carried out on sheet metal wiring shelves, fitted at the

Fig. 6.—Open cut north of Davisville showing automatic signal N316, point machine 102A, train stop, dwarf signal and key-by unit.

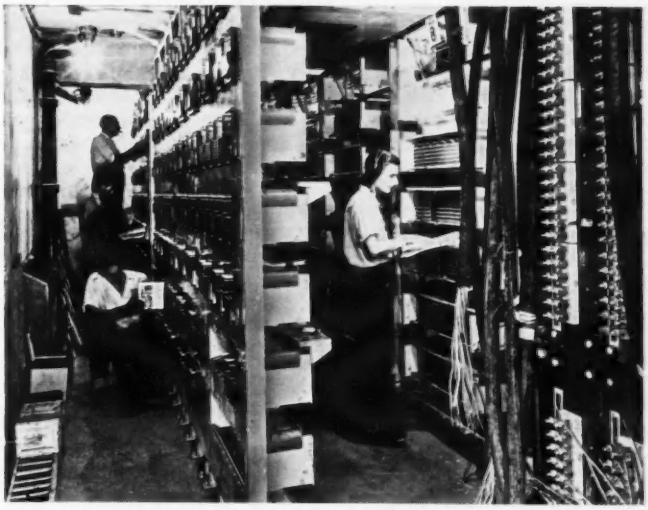

Fig. 7.—Relay room at Davisville during wiring.

rear of the racks, one wiring shelf equipped with a removable protective cover being provided for each row of relays ; the ends of the racks are fitted with enclosed vertical wiring ducts. All metal work, racking and ducting is finished in a cream coloured protective paint.

AUTOMATIC SECTIONS.

Three aspect signalling is used to control traffic flow in the automatic section between Union and Davisville interlockings. To obtain a two-minute headway between trains, 60 signals with train stops are spaced at calculated distances along both tracks of the 3¼ miles separating the limits of the interlocking installations.

Time control of signals is used to supplement their normal block section control where operating conditions make it necessary to enforce a rigid check on running speeds, as in the case of a 90° curve in the line approaching Union Station where, under certain conditions, a lunar white marker light is illuminated on the signal controlling entry to the curve to indicate that the signal ahead will clear if the allowable speed limit is observed ; this is referred to as ' grade time control '.

Automatic signals can be passed at ' stop ' in accordance with the provision of a ' stop and proceed with caution ' rule, the train stop arm being automatically lowered after the train has been proved to have come to rest at the signal (fig. 8).

Fig. 8.—Automatic signal in tunnel.

EMERGENCY CROSSOVERS.

Between Union and Davisville, in the automatic section, there are altogether four emergency reversing crossovers equipped with hand-throw point machines which have electric ground locks and point detection. A release to free the ground lock is obtained from a control panel housed in a metalclad compartment fitted on top of the crossing apparatus cases located at either end of the crossover. Mounted on the control panel face are keys for selecting the type of move to be under-

taken, i.e. either a ' reverse traffic ' or ' turning ' move, and lamps indicate conditions of the approach track circuits, the setting of the next emergency crossover ahead, and the ' lock free ' condition. A control panel for emergency crossover, and a hand-throw point machine are illustrated in figs. 9 and 10 respectively.

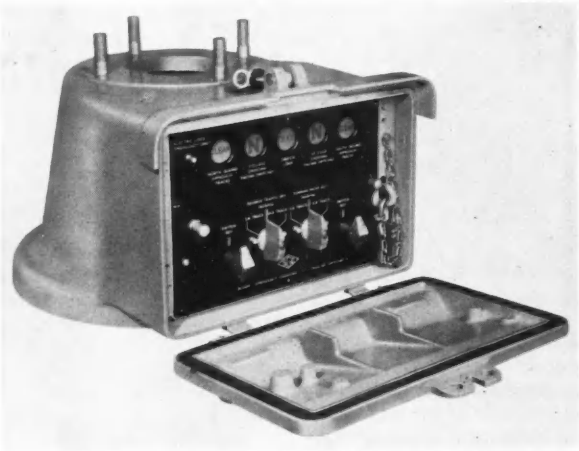

Fig. 9.—Control panel for emergency crossover.

SIGNALS.

All running signals are of the three aspect multi-lens colour light type displaying either green, yellow or red ; a green aspect being illuminated for the main or through route and a yellow aspect for a diverging route (fig. 11).

Each signal in the interlocking area comprises three units, the upper unit, of three aspects, is interpreted by the motorman in the same way as those in the automatic signals previously described, while the middle unit, also of three aspects, is intended to describe the route to be followed. The lowest unit is a call-on aspect, which when operated clears to a yellow to warn the motorman that he has to stop and operate a ' key-by ' unit (a manually operated circuit controller) fixed on the track side within reach of the driving compartment window, in order to lower the train stop arm at that signal.

In some instances traffic operation permits the lowering of the train stop arm automatically with the clearance of the call-on signal, in this case the signal displays a flashing yellow aspect.

The intensity of the light beam of all outdoor controlled signals at Davisville can be reduced by operating a dimming switch on the control panel.

To withstand rigorous winter conditions all outdoor signal heads have been soundly gasketed to prevent the ingress of moisture. In view of the restricted clearance inside the subway the lens diameter adopted on all signals is $6\frac{3}{8}$ in. The lens system for outdoor signals consists of a standard doublet combination ; close-up indications are provided by means of prisms moulded in a sector of the outer lens. For tunnel signals the coloured inner lens is not stepped, and provides a wide spread beam. All signal and route indication lamps are British Standard SL.22, 12 volts, 10 plus 4 watts.

Signal number plates are in the form of an illuminated stencilled lens unit in tunnel sections, accommodated in a separate lamp compartment in the same casting as the three-aspect signal ; in outdoor sections enamelled iron number plates are used. All signals have a ' location ' number and, in addition, an interlocking number prefixed with the letter X is provided on interlocking signals.

Dwarf ground two-aspect colour light signals, suitably inclined back

Fig. 10.—Hand-throw point machine as used for switching emergency crossover.

from the vertical and mounted on top of small apparatus cases, govern outlet moves from Davisville yard. A tunnel mounted automatic signal is seen in fig. 12.

TRAIN STOPS.

The train stops used in conjunction with each running signal are for alternating current operation on the 110 volts, 60 cycle supply. They are operated by a single-phase, capacitor induction motor and the weight of the motor is used to return the trip arm to the tripping position when de-energised.

Two types of layout are employed. In the first, where the rails are on ties (sleepers) and ballast, the motor units are mounted between the running rails and the drive to the trip arm is by means of an extended shaft to the outside of the running rail.

The second, in the tunnels, where the rails are mounted on rubber pads and held directly to the floor of the tunnel, the motor units are mounted in a recess in the 'cat-walk' at the side of the tunnel and the drive to the trip arm, which is separately mounted, is by means of a link motion.

The trip arm heads are detected in the tripping or clear position by means of a circuit controller and provision is made that, should the trip arm head be broken off, then the proving of the head is disrupted.

Both motor units and circuit controllers are housed in substantial weatherproof cases and those mounted in the open sections are provided with heaters for use in adverse weather conditions to ensure freedom of operation.

POINTS.

Both power-operated and manually switched point layouts are used. There are 24 layouts of the former, each operated by a 110 volts D.C. machine of the combined type, comprising the motor drive mechanism, point locking device, and switch tongue detector contacts housed in a single unit. The 110 volts D.C. main supply is fed to the motor over the contacts of a continuously energised plug-in type point contactor relay, housed adjacent to the machine.

Hand cranking facilities provide a means of operation in the event of an emergency. On resumption of normal operation special cut-off arrangements prevent the motor being energised, even should the crank handle be withdrawn, until a reset plunger on the machine is manually released.

Electric heaters are fitted inside the point machines in the open section to maintain a favourable operating temperature during the periods of severe winter weather. Point layout in Davisville yard is seen in fig. 13.

The hand-operated machines, of which there are 16, are installed at the emergency cross-overs, and each is a self-contained unit enclosing the point locking device, throw mechanism, detector contacts, and an electric ground lock, in the same casting. Again, where called for, internal heaters are fitted.

TRACK CIRCUITS.

Because one of the running rails is used for the return of traction current, single rail track circuits of the alternating current condenser fed type are installed on all running lines. There are 103 sets of track circuit equipment consisting of a 1/1 feed isolating transformer, a 20 μF

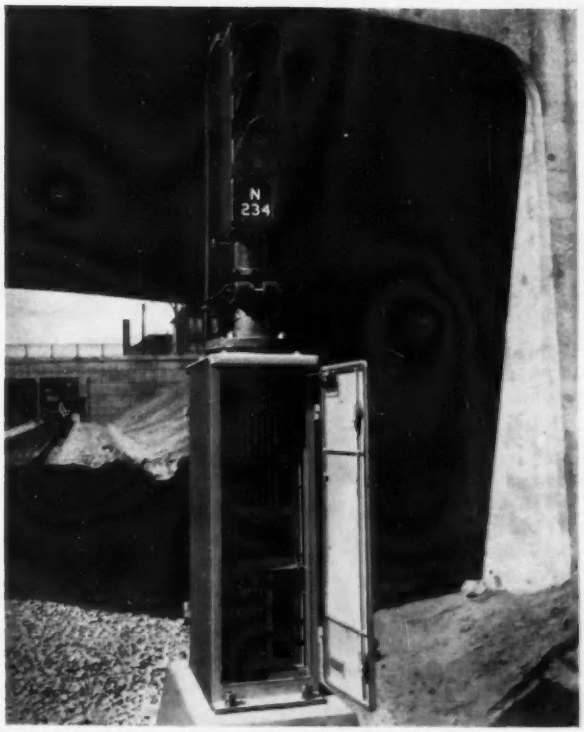

Fig. 11.—Three-aspect interlocking signal mounted on apparatus housing at a tunnel portal.

adjustable condenser and a double element vane track relay.

The relay and feed wires to the rails are connected, first, to bootleg posts from which bare flexible bond wires are welded on to the outer edge of the running rails.

In Davisville yard transformer fed lamp indication track circuits are installed which operate

Fig. 12.—Tunnel-mounted automatic signal with train stop in 'cat-walk' recess.

when a train has been drawn up to within a close distance of an outlet ground signal.

Where electric snow-melting devices, working off the 600 volts D.C. traction supply, are installed, the track relay is protected by a resonated isolating transformer. This is done as a precaution against damage to the relay which might arise if faulty insulation on the snow-melting track jumpers caused an excessive voltage to appear on the signalling rail.

RELAYS.

The 920 signalling relays employed throughout the installation are of the standard S.G.E. plug-in type, and are either single or double width according to their functional arrangements and contact capacities.

Locating pins prevent the insertion of a relay of an incorrect type into a mounting plate; when a relay is correctly plugged in it is mechanically latched and cannot be removed unless the latch be released.

APPARATUS HOUSINGS.

In all, some 126 apparatus housings are fixed at the track side. These housings serve a double purpose in that they have accommodation for equipment such as relays and transformers, etc., and, in addition, the terminals necessary for the termination of power supply and signal control cables.

Each housing is constructed in two units, an outer shell of fabricated steel and an inner framework with fittings for plug-in relays, transformers, condensers and such-like equipment, together with appropriate terminals.

The reason for this arrangement was twofold, the outer shells were completed and shipped from England to site and were ready for immediate installation which enabled the erection of signals to proceed. In the meantime the inner frameworks, consisting of a main frame into which a second framework was fixed by means of resilient mountings, were assembled. All equipment was then fixed to the latter frame, wired and tested in the factory before export to site. The installation of a completely equipped and wired inner unit was then a small matter and it only remained for the cables to be connected. Wiring for cable terminations and a front interior view of the completed apparatus case are seen in figs. 14 and 15 respectively.

POWER SUPPLY.

The power for the signalling system is obtained from seven local supply sources spaced along the route of the subway. Each local feeding point provides a 'normal' and an 'emergency' supply at 208 volts, 60 cycles, single phase, A.C.

The seven power distribution rooms, usually situated on platforms, but in the cases of Union and Davisville in the interlocking signal cabins, contain transformers and automatic transfer

cubicles for the 110 volts, 60 cycle signalling mains. The transfer apparatus serves to connect the emergency supply when the normal supply voltage drops below any pre-set value between 75 per cent and 90 per cent of normal, and reconnects the normal supply when this has been restored to 95 per cent or more of the normal voltage for a predetermined period, and has been specially designed to effect rapid transfer of loads.

For the D.C. signalling supplies, two transformer rectifier sets, each fed from one of the two mains transformers, provide the 24 volts required for energising the interlocking and line relays.

The 110 volts direct current for operating the point machines at Union and Davisville is obtained from a battery, charged from the alternating current main.

Also at these two interlockings and at Eglinton are alarm relay sets which translate into a visual form on the interlocking control panel the condition of the various supplies, 'power off' and 'ground' indication being supplemented by an alarm bell.

Ground detection equipment is installed at all supply points, and separate detectors are provided for each supply, namely 110 volts A.C. and 110 and 24 volts D.C.

POWER DISTRIBUTION.

Distribution of the signalling power is by means of twin-core A.C. and D.C. mains, one for each track, which extend in both directions from each power room, approximately halfway to each adjacent power room.

All track circuits, signals and other control circuits required to allow a train freely to enter a station, receive the energy from the same section of mains which feed the signals governing train movements in the approach to the station. This is to provide for uninterrupted train movement into a station in the event of a failure of the adjacent section of power main (in the direction of traffic).

In general, the signal mains in the subway are suspended from messenger wire, while in open section they are buried.

WIRING IN RELAY ROOMS.

It was decided that the most satisfactory arrangement would be for the whole of the relay rack wiring to be carried out on site rather than in the factory, as, due to the number of relays to

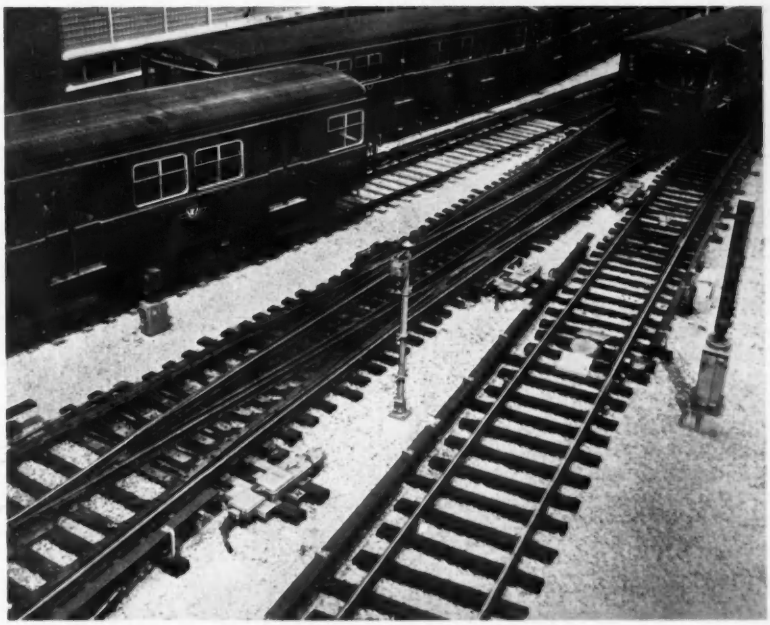

Fig. 13.—Double slip and movable diamond layout in Davisville yard ; also illustrated are a dwarf signal, an interlocking signal, key-by unit and train stop.

be accommodated, the total weight of each complete rack would have made shipping to, and handling on, site impracticable.

Reference has already been made on page 240 to the relay racks, from which it will have been gathered that an individual rack is capable of

Fig. 14.—Wiring for cable terminations.

accommodating only a given number of relays and that at each interlocking several such racks were necessary. It will be seen from the foregoing that it would have been possible to wire in the factory only the equipment on that particular rack. Connecting wires to other racks or to the main termination boards, would have had to be installed on site.

While electrical wiremen were available in Canada, they were not necessarily trained in reading wiring diagrams drawn up in accordance with standard practice in the railway signalling field. However, experience had shown that these qualifications were unnecessary, for a simple method ensuring quick and accurate wiring had already been devised and proved to be practical. All wiring was installed and terminated in accordance with instructions shown on a printed schedule, together with the wire identification labels. In all, approximately 30,000 such labels were provided. All multi-core cables entering relay rooms or apparatus housing were identified by black fibre labels, and of these some 12,000 were used. Fig. 16 shows the wiring of a relay room.

EQUIPMENT AND INSTALLATION.

All the signalling equipment was manufactured in England to the requirements laid down in the Toronto Transit Commission specification and contract drawings, with the exception of cables and cable run accessories, which were purchased in Canada. Installation drawings, wiring schedules and diagrams and any other information in this connection were produced in England.

The whole of the installation was carried out by a Canadian labour force to the satisfaction of a supervising engineer and an assistant, both sent from England. A third engineer followed at a later date to assist with the testing.

Installation work began on site late in 1952 and was completed in January, 1954.

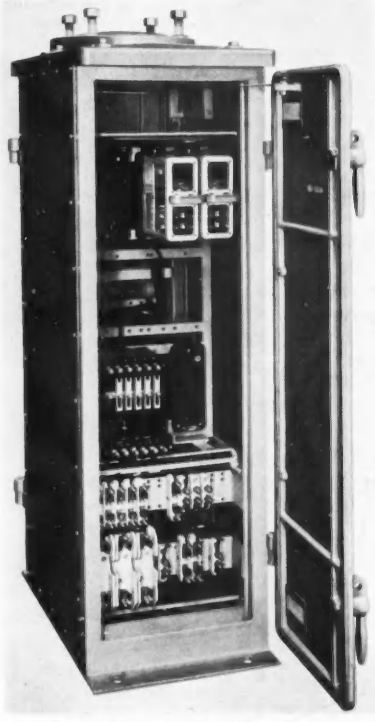

Fig. 15.—Front interior view of completed apparatus case showing plug-in and other equipment.

TESTING.

Preliminary testing began with the checking of all outside cables both for insulation and correct terminating. Track circuits were connected to rails and checked for correct operation ; this was followed by the proving of circuits to signals, train stops, point machines, etc. With the completion of relay room wiring, tests were begun at the interlockings.

In order to facilitate this, a special switch or key cabinet with indicating voltmeters was fixed in a convenient position near to the control panel. The cabinet was equipped with two and three position keys, each with a plain ivorine nameplate to be marked as required. A multicore switchboard cable was connected to the keys, and the other end was wired to the main terminal board in the relay room or to a particular piece of equipment prior to the commencement of a test. By this means it was possible to check fully all circuits from the control panel to the relay room and to the outgoing terminals carrying the controls to the outside functions such as signals, points, and so forth.

It will be seen that it was now possible to simulate the operation of all outside apparatus which would be controlled from the control panel. Thus, when checking a particular circuit, a key might be used to operate a track relay to its clear or occupied position, or a point detection relay to normal, reverse or de-energised position as required without having to operate the actual points or by using false feeds and so on. The small amount of time required to set up the key panel was amply justified by the results.

The voltmeters were connected by long leads to the various circuits under test so that the testing staff had visual indication of the response or otherwise of the function under test.

CONCLUSION.

The Toronto Rapid Transit subway was opened and successfully brought into use on March 31st, 1954, after some weeks of train operation to schedule, designed for the purpose of instructing motormen and traffic operating staff.

By the close co-operation of all concerned the work of installing S.G.E. signalling equipment on a site so remote from England was made easier than one would imagine. In this respect particular tribute must be paid to the Chief Engineer of the Toronto Transit Commission, Mr. W. H. Paterson, and his staff.

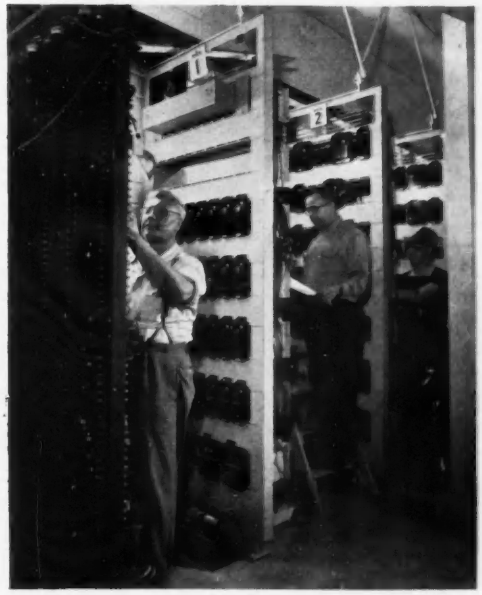

Fig. 16.—Wiring plug-in relay racks in the Davisville relay room.

TECHNICAL LITERATURE

A DIGEST OF RECENT BOOKS, ARTICLES AND PAPERS, BY MEMBERS OF THE G.E.C. AND ITS ASSOCIATED COMPANIES

THERMOSTATS FOR MOTOR PROTECTION.

By A. R. Blanchard (Salford Electrical Instruments, Ltd.).

Electrical Times, December 10th, 1953.

Motor protection thermostats are now fitted to many fractional horse-power motors used in factories and workshops and to motors in domestic appliances, such as washing machines and refrigerators. Unlike fuses and magnetic relays, which are essentially current-operated devices, and simple thermostats, which are essentially temperature-operated, motor protection thermostats operate on both current and temperature. By choosing a type with suitable characteristics the motor can be protected against overheating in the windings no matter how arduous and varied the conditions under which it works.

CONTRIBUTIONS TO THE STUDY OF RECTIFIER AND NETWORK HARMONICS AND THEIR EVALUATION FOR TRACING THE SOURCE OF WAVE DISTORTIONS.

By E. Friedlander, Consulting Engineer, (Witton) and W. G. Thompson (Witton Laboratory).

It is found that the two harmonics of rectifiers, the order of which is adjacent to the phase number of the rectifier, are both strongly interlinked with the D.C. circuit, and therefore with each other. This leads to a new equivalent circuit for the generation of rectifier harmonics which agrees with the conventional picture only in the limiting case of complete smoothing of the direct current. The second part of the paper shows methods for discriminating between harmonics of different origin.

FLAMEPROOF, PRESSURISED AND INTRINSICALLY SAFE LIGHTING EQUIPMENT.

By Hugh S. Allpress (Illuminating Engineering Department).

Light and Lighting, Vol. XLVI, No. 12, 1953.

The article is a review of current industrial practice and draws attention to the most notable recent developments in equipment to meet with present-day statutory requirements which are also discussed. It is emphasised that, in a wide range of gases where all serious electrical equipment had provisionally been prohibited, normal electric lighting can now be installed by making use of the new approved pressurised system.

A NEW APPROACH TO THE DESIGN OF SUPER-DIRECTIVE AERIAL ARRAYS (526).*

By A. Bloch, R. G. Medhurst and S. D. Pool (G.E.C. Research Laboratories).

Proc. I.E.E., Vol. 100, Part III, No. 67, 1953.

The current distribution required for maximum directivity of an array with a finite number of elements and any specified geometrical configuration is shown to be completely defined by the self- and mutual - resistances of the elements and by a certain component of the voltage (the "resistance voltage") across the terminals of each element. This voltage component is required to vary from element to element in the same way as the instantaneous local values of a sinusoidal disturbance travelling across the array, in the direction under consideration, with the velocity of an electromagnetic wave.

As a consequence, the maximum gain of the array is expressible either as a double sum containing only the mutual conductances between the individual elements multiplied by trigonometrical factors depending on their spacing, or as an expression identical (except for a numerical factor) with that for the distant field of the array.

These theorems hold, slightly modified, for arrays of non-identical elements.

THE ATOMIC POSITION AND SIZE OF THE THALLIUM IONS IN KCl(Tl) PHOSPHORS (533).*

By W. A. Runciman and E. G. Steward (G.E.C. Research Laboratories).

Proc. Phys. Soc. "A", Vol. LXVI, p. 484, 1953.

A new X-ray investigation has been made of the KCl(Tl) phosphor in view of the discrepancy between the early theory of Fromherz involving formation of complexes in the KCl(Tl) phosphor and the recent theoretical work of Williams, in which substitutional entry of the thallium ions is assumed. The present study has now shown (*a*) that the expansion of the potassium chloride structure due to the incorporation of thallium is in agreement with Vegard's law and (*b*) that Tl+ ions enter the structure substitutionally. The present results differ from those obtained by Stasiw and Saur in a less detailed X-ray study. The intensities of X-ray reflections have also been used to establish the atomic position of the activator atoms in the phosphor and the results fully confirm the interpretation of the observed lattice expansions.

A new value of 1·42$_7$ Å has been obtained for the ionic radius of the Tl+ ion in sixfold co-ordination with Cl− ions. This is of importance in the detailed calculations of the luminescence of KCl(Tl) which have been made by Williams and others.

AN AUTOMATIC RECORDER OF AERIAL RADIATION DIAGRAMS (572)*.

By E. G. Hamer, B.Sc. (Eng.), A.M. Brit. I.R.E. and J. B. Lovell Foot, A.M.I.E.E. (G.E.C. Research Laboratories).

Journal of The British Institution of Radio Engineers, Vol. XIV, No. 1, January, 1954, pp. 33-42.

The requirements of a machine which will plot the radiation pattern of aerials automatically are briefly outlined, and a design that meets these requirements is then described. The basis of the design is the automatic comparison of a local audio-frequency signal, and a signal of the same audio-frequency proportional to the unknown radio-frequency signal. Such a system has the advantage of being readily adaptable for a wide range of radio-frequencies. Arrangements are made for mounting large aerials at various heights and for the presentation of results in different ways. Facilities are also provided for indicating the relative field intensity when it is desired to plot by hand.

*** A limited number of reprints is available of those papers marked with an asterisk. Copies may be obtained on application to the Editor, G.E.C. Journal, Magnet House, Kingsway, W.C.2.**